CRANFIELD UNIVERSITY

JAMES E GAUTREY

FLYING QUALITIES AND FLIGHT CONTROL SYSTEM DESIGN FOR A FLY-BY-WIRE TRANSPORT AIRCRAFT

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SUPERVISOR: M V COOK

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Abstract

Fly-by-wire flight control systems are becoming more common in both civil and military aircraft. These systems give many benefits, but also present a new set of problems due to their increased complexity compared to conventional systems and the larger choice of options that they provide. The work presented here considers the application of fly-by-wire to a generic regional transport aircraft.

The flying qualities criteria used for typical flying qualities evaluations are described briefly followed by analysis of several past transport aircraft flying qualities programmes against these criteria. From these results, some control law independent design requirements are formulated for a civil aircraft for the approach and landing task. These control law independent flying qualities criteria are intended to be used with any generic rate-like control law for a transport aircraft and enabled a number of different control laws to be designed.

The results of a number of flying qualities evaluations are presented. Both an ILS approach task and a formation flying task were used. The effects of windshear were also considered. It was found that control laws which maintain flight path are suitable for the ILS approach task, while most rate-like response characteristics give good flying qualities for the formation flying task.

Finally, the conclusions drawn from these evaluations are presented, and both the Civil and Military current airworthiness requirements are assessed.

In addition to the flying qualities work, a study is made of the management issues associated with fly-by-wire design. A fly-by-wire aircraft design programme was proposed and the project management issues associated with this were considered. A timescale was proposed for the design process for a generic regional aircraft, and the critical path for this process is presented.

Dedication

This thesis is dedicated to my parents.

The Future

> It is not really necessary to look too far into the future. We see enough already to be certain that it will be magnificent.

Wilbur Wright, Paris 1908.

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List of Notation and Abbreviations

Notation

α	Angle of Attack
Δ	Denominator
δ_e	Elevator Angle
ϵ	Error Signal
γ	Flight Path Angle
γ_{eff}	Effective Flight Path Angle
γ_{esh}	Change in Effective Flight Path Angle Due to Wind Shear
γ_{est}	Effective Flight Path Angle Due to Constant Headwind
γ_i	Inertial Flight Path Angle
η_d	Elevator Demand
ω_{lt}	Long Term Mode Natural Frequency
ω_{ph}	Phugoid Mode Natural Frequency
ω_{sp}	Short Period Mode Natural Frequency
ω_{st}	Short Term Mode Natural Frequency
τ	Time delay
θ	Pitch attitude
$\ddot{\theta}_{init_{max}}$	Maximum Initial Pitch Acceleration
ζ_{lt}	Long Term Mode Damping Ratio
ζ_{ph}	Phugoid Mode Damping Ratio
ζ_{sp}	Short Period Mode Damping Ratio
ζ_{st}	Short Term Mode Damping Ratio
ALPHA	Actual Angle of Attack
ALPHATRIM	Trimmed Angle of Attack
D	Drag
dB	decibel
DE	Elevator Angle
DEN	Denominator
DEN_{ACT}	Denominator Actuator
F_e	Longitudinal Control Force
F_s	Longitudinal Control Force
G	Gravitational Acceleration, 9.81 m/s^2
g	Gravitational Acceleration, 9.81 m/s^2
kt	Knot
K	A Simple Gain
L	Lift
m	Mass

N	Numerator
$N_{\delta e}^{\alpha}$	Angle of Attack to Elevator Transfer Function Numerator
$N_{\delta e}^{\gamma_{PS}}$	Pilot's Station Flight Path to Elevator Transfer Function Numerator
$N_{\delta e}^{\theta}$	Pitch Attitude to Elevator Transfer Function Numerator
NUM_{ACT}	Actuator Numerator
Nz	Normal Acceleration
q	Pitch Rate
q_{MAX}	Maximum Pitch Rate
q_{SS}	Steady State Pitch Rate
s	second
s	Laplace Operator
t_{γ}	Flight Path Time Delay
T	Thrust
T_{γ}	Flight Path Angle Transfer Function Zero
T_{θ}	Pitch Attitude Transfer Function Zero
T_{θ_2}	Pitch Attitude Transfer Function Zero
T_{a_1}	Angle of Attack Transfer Function Zero
THETA	Actual Pitch Attitude
THETAREF	Reference Pitch Attitude
V_{air}	Airspeed
V_{REF}	Reference Approach Airspeed
VAIR	Actual Airspeed
VTRIM	Trimmed Airspeed
V	Airspeed
W_{X}	Horizontal Wind Velocity
W	Weight
y	Output
y_{d}	Demanded Output

Abbreviations

3-D	3-Dimensional
ACE	Airbus Concurrent Engineering
ADIRS	Air Data and Inertial Reference System
AIAA	American Institute for Aeronautics and Astronautics
ATC	Air Traffic Control
BAe	British Aerospace
C*	C* Control Law
C*α	C* with Trim to Angle of Attack Control Law
C*U	C* with Trim to Airspeed Control Law

C/L	Control Law
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacture
CAMU	Concurrent Assembly Mock-Up
CAP	Control Anticipation Parameter
CATIA	Computer Aided Three Dimensional Interactive Application
CG	Centre of Gravity
CHR	Cooper Harper Rating
CoA	College of Aeronautics
CTOL	Conventional Take-Off and Landing
DB	Pitch Attitude Dropback
DBT	Design / Build Team
Dec	Decade
DEF STAN	Defence Standard
DFMA	Design for Manufacture and Assembly
DLC	Direct Lift Control
DOC	Direct Operating Cost
DSE	Dynamic Systems Engineering
EAP	Experimental Aircraft Programme
EDM	Enterprise Data Management
EFIS	Electronic Flight Information System
ETPS	Empire Test Pilots School
FADEC	Full Authority Digital Engine Control
FAR	Federal Airworthiness Requirements
FBW	Fly-By-Wire
FCS	Flight Control System
FMS	Flight Management System
GCAP	Generic Control Anticipation Parameter
GRA	Generic Regional Aircraft
H/W	Hardware
HUD	Head-Up Display
Hz	Hertz (1 cycle/sec)
IDA	Institute for Defense Analysis
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IPDT	Integrated Product Development Team
IRAD	Internal Research and Development
ISO	International Standards Organisation
JAR	Joint Airworthiness Requirements
LOES	Low Order Equivalent Systems
MIL-STD	Military Standard (US Department of Defense)
MOFQ	Mission Oriented Flying Qualities

N1	Fan Speed for Turbofan Engine
NASA	National Aeronautics and Space Administration
NC	Numerically Controlled
NLR	National Aerospace Laboratories (the Netherlands)
NS	Neal-Smith
Nz	Normal Acceleration Control Law
Nzα	Normal Acceleration with Trim to Angle of Attack Control Law
Nz$_{SS}$	Steady State Normal Acceleration
NzU	Normal Acceleration with Trim to Airspeed Control Law
P+I	Proportional + Integral
PAPI	Precision Approach Path Indicator
PIO	Pilot Induced Oscillation
q	Pitch Rate Control Law
qα	Pitch Rate with Trim to Angle of Attack Control Law
QFD	Quality Function Deployment
qU	Pitch Rate with Trim to Airspeed Control Law
RAe	Royal Aircraft Establishment
RAF	Royal Air Force
RCAH	Rate Command Attitude Hold
S/W	Software
SPC	Statistical Process Control
SWAT	Subjective Workload Assessment Technique
TIFS	Total In-Flight Simulator
TLX	Task Load Index
TPS	Test Pilots School
TQM	Total Quality Management
US DoD	United States Department of Defense
USAF	United States Air Force
V/STOL	Vertical Take-Off and Short Landing
VFR	Visual Flight Rules
VMS	Vertical Motion Simulator

1 Introduction

Many changes have occurred in the past 20 years in aircraft manufacture and development. New technologies have appeared, spanning the entire aircraft design environment, such as new production methods, new materials and new avionics systems. These new methods have been developed for two reasons. For military aircraft, they have arisen through the need to improve performance. However, for civil aircraft they have arisen through the need to reduce the overall cost.

This thesis considers one aspect of these technologies for civil aircraft: fly-by-wire. This technology uses electrical signalling in place of conventional heavy mechanical control runs. In addition, fly-by-wire generally permits improvements to be made in aircraft flying and handling qualities. This requirement has originated from two main sources; a need to make improvements in the light of an increasing amount of experience, and a requirement to cope with aerodynamic modifications which have been implemented to improve aerodynamic efficiency, but which have a deleterious effect on the aircraft's flying and handling qualities. Both of these adverse effects have come about from a desire to reduce costs for the aircraft's users, the airlines.

The aircraft used for these evaluations is a Generic Regional Aircraft, of about 100 seats and a weight of 90,000 lbs. Only a limited portion of the flight envelope was considered since these evaluations primarily concentrate on the approach and landing flight phase. It has a low wing with twin under-slung engines, and it has a conventional tail. This is similar to the Airbus A320 shown in figure 1.1 (from Airbus Industrie Website), and the Boeing 737 shown in figure 1.2 (from the Boeing Company Website).

These evaluations are being carried out as part of a joint Avro International Aerospace – Cranfield University Engineering Doctorate programme researching advanced flight control system design for a Generic Regional Aircraft. The overall aim of this programme is to produce a flight control system design which gives aircraft in question excellent flying qualities. The evaluations described here comprise the first in a series of three planned studies, and consider solely the approach and landing flight phase.

1.1 Handling and Flying Qualities

This thesis primarily considers handling and flying qualities for the Generic Regional Aircraft. Handling qualities describe the airframe / flight control system response characteristics. Flying qualities are considered to be slightly different since the task and other relevant factors such as cockpit display design are considered.

Figure 1.1: American West Airbus A320 (from Airbus Industrie Website)

The definition of good handling and flying qualities is not easy to make as both encompass many aspects of aircraft design and operation. However, Ashkenas [3] describes the following qualities which are often associated with good aircraft flying and handling qualities:

1. Trim and unattended operation - the pilot must be able to trim the aircraft so that it will fly "hands off";
2. Large amplitude manoeuvres - the pilot must be able to perform or control large amplitude manoeuvres from given cues;
3. Regulation and precision flying - In closed loop control, the pilot must be able to hold the aircraft on a desired trajectory in the presence of disturbances, such as gusts.

All of the elements of the pilot - aircraft closed loop system need to be considered [4]. This is because the effects of display design and other pilot-machine interfaces have a large effect on the aircraft's flying qualities. This includes the effects of inceptor characteristics, such as whether a sidestick or centre control wheel is used. For these evaluations, only a centre control wheel is used. Other aspects of information flow such as display design and pilot to pilot communication are briefly considered.

For the purposes of this work, the term 'aircraft' refers to the basic airframe together with any augmentation which may modify its flying qualities. The augmentation is

Figure 1.2: Boeing 737-700 (from the Boeing Company Website)

nominally referred to as a 'control law', which modified the aircraft's flying qualities, and is usually represented as software in the aircraft 'flight control system'. The flight control system is the hardware and software which modifies the characteristics of the airframe.

The primary driver behind flight control system design is to obtain the best performance out of the pilot-aircraft combination. Therefore the aircraft and its associated system should be designed around the pilot, which is known as 'human centred design'. Pilot situational awareness, or the way in which the aircraft conveys information to the pilot is also of crucial importance and this is also considered in this thesis.

External disturbances such as atmospheric effects and Air Traffic Control (ATC) requests also need to be considered, as recommended by Field [4]. The reasons for this are that gusts can have a pronounced effect on the perceived aircraft handling and flying qualities, it can drastically modify the pilot ratings and therefore may have a significant effect on the final response type choice. In addition, there are many constraints placed on aircraft by ATC, and a control law which prevents the aircraft from achieving these requirements is obviously not suited to the task which it is required to accomplish. However, these external disturbances have been ignored for these evaluations as they may initially obscure the underlying characteristics being evaluated, and it is planned to consider them in a subsequent set of evaluations.

1.2 Initial Flying Qualities Research

Much of the initial flying qualities research originated for military fighter aircraft from the desire to improve aircraft performance, and thus gain superiority over the opposition. The technologies which were being used to produce modern flight control systems were still expensive though, and had yet to evolve to the civil aircraft manufacturers. Therefore little work was initially done on civil aircraft flying qualities; the majority was performed for military aircraft, primarily fighters.

As the technologies matured, they started to find application to modern civil aircraft. Also, the drive to improve flight safety made the civil aircraft manufacturers take note and to start looking at handling and flying qualities more seriously. Therefore more research programmes aimed at transport aircraft (both civil and military) were carried out, which greatly expanded the limited information database. However, much of the data is still only applicable to fighter aircraft, and therefore must be treated with caution when considering large civil aircraft.

The piloting tasks for civil and military aircraft may be drastically different. With fighter aircraft, a large number of the flying qualities investigations concentrated on pitch pointing tasks, which are relevant to the majority of the weapon aiming and in-flight refuelling tasks. However, civil aircraft flying qualities investigations have tended to concentrate on the approach and landing task, since this is considered to be the most critical piloted flight phase for a civil aircraft. This is a substantially different task to a pitch pointing one, and necessitates a different set of requirements.

Many different aircraft have been evaluated over the past 30 years in a variety of variable stability aircraft and in-flight simulators. These have evaluated many variations on the dozen so so response types. Since it is obviously impractical to evaluate every one of these for the current programme, some initial selection was performed.

1.3 Previous Flying Qualities Research at Cranfield

As previously stated, the aircraft under consideration here is a Generic Regional Aircraft. Previously, work has been performed at Cranfield [4] on this type of aircraft, again looking at the approach and landing phases. This programme considered command concepts and their applicability to the same Generic Regional Aircraft. Field isolated some of the key characteristics which are relevant to the approach and landing task for a variety of different response characteristics. This thesis builds on that work by applying those 'key concepts' to the different control law types which are implemented in actual aircraft.

Therefore, the different control laws being evaluated for the purposes of this thesis are based on the actual response types which have been implemented on existing fly-by-wire aircraft. This follows on from Field's work [4], which considered generic command concepts for a Generic Regional Aircraft. Therefore, as well as current control law types, additional control laws will be evaluated which follow on directly from the current laws in use and the results of Field's work.

From his work, it is clear that there are fly-by-wire control strategies where follow-on studies would be beneficial. Hence it is also proposed, for example, that the issue of speed stability in the approach flight phase be considered after the initial evaluation work. The scope of the programme will be determined from the results of an initial review, together with the final conclusions from Field.

Since the control laws to be designed here are representative of actual control laws used in practice, this implies that the control law structure will be representative of an actual flight control system, but excluding features such as structural filters. Also, limits are placed on the sensing requirements and this will be taken into account when defining the structure of the control laws. A notional flight control system hardware architecture is available for this aircraft [5], and this is considered when the control law architecture is designed.

Angle-based response types such as pitch attitude demand or flight path angle demand systems (but with the exception of angle of attack) will not be evaluated for this thesis. They can give good qualities for a given trim point, but they have high trimming requirements associated with them, which goes against the requirement for minimal trim changes for flight path change. Field [4] found that angle command laws were rated worse than the corresponding rate command law for the approach task. Also, they are not currently used in practice as the principal command concept for any aircraft, with the exception that they have been used in the flare in previous flying qualities studies to give conventional characteristics, as previous studies have shown.

The importance of the long term response of the aircraft is also considered for these evaluations. Airspeed control has been assessed by considering the effects of an autothrottle. An artificial long term mode can be introduced by feeding speed error back to the pilot's demand. This was assessed for the control laws evaluated here.

During the design process, the effect of higher order systems and alternative response types need to be considered since a particular flying qualities criterion which may be valid for one command concept and flight phase may not be valid for a different one. This is another conclusion from Field's work [4], and is also considered by French [6] in the form of Mission Oriented Flying Qualities (MOFQ). French makes the point about task tailoring, in that an aircraft's flying qualities must be tailored to the task which the aircraft is being used for. Task tailoring is also a strong theme throughout Field [4]. Therefore the flying qualities evaluations are broken down into distinct phases so that the suitability of each law to each phase may be considered.

1.4 Mission Oriented Flying Qualities Requirements

Clearly, one of the most dominant factors in aircraft flying qualities design is the dynamic response of the airframe / flight control system combination. This response ties in with the task under consideration and other aspects of the aircraft such as the pilot's displays to give a set of characteristics known as flying qualities.

The flying qualities design requirements are dependent on many factors, but one of the most important is the aircraft mission. It is imperative that the aircraft's flying qualities are designed with the aircraft's mission in mind, since the requirements for the landing task of a large transport aircraft are different to those for a highly manoeuvrable fighter aircraft in the air-to-air combat task. Therefore, Mission Oriented Flying Qualities (MOFQ) have arisen out of the need to be able to tailor an aircraft's flying qualities to the required task.

Modern flight control systems are capable of making an aircraft behave in a very non-conventional manner, conventional being a well-behaved classical aircraft with no augmentation. This results in many different control strategies being developed, of which some are more suitable than others. The work undertaken here has been done from the viewpoint that control strategies can be made to behave in different ways, and therefore the factors which are relevant to good handling and flying qualities should be extracted, and incorporated into a flight control system design. It should therefore be possible to enable most control strategies to be implemented, and behave reasonably well, although there will still be limitations imposed by the strategy itself which may differentiate between the different strategies.

Therefore the factors which are 'strategy independent' have initially been covered, and then these key factors have been incorporated into the individual strategies. The definition of the task is fundamental to the evaluation of aircraft flying qualities. Suitable task definitions can be found in appendix C contained within reference [1].

1.5 Flying Qualities Evaluation Tasks Under Consideration

Initially the control laws under consideration were evaluated using a reconfiguration, approach and landing task. In addition, the effects of autothrottle were considered since the majority of civil transport aircraft will be flown with the autothrottle engaged. This gave an airspeed range of 140 to initially 121 knots on the approach, and then down to 115 knots in the flare.

However, this obviously does not cover the entire aircraft airspeed range, but since the approach and landing task is generally accepted to be the most critical task for a civil aircraft, it is deemed a suitable task for evaluating the control laws under consideration. However, civil aircraft manufacturers also use other tasks for the evaluation of control laws since there is a requirement to test the laws over the full flight envelope. For example, several different tasks were used for evaluation during the design of the Boeing 777, including a variety of approach tasks, en-route tasks, and in-flight tracking type tasks.

Therefore a formation flying task was proposed as a suitable task for evaluating control law performance at altitude for the generic regional aircraft. It was initially thought to be a tight flight path control task, and this was quickly confirmed from a brief trial prior to the main evaluations. In addition, this task is one which is the most demanding for a large military aircraft since it requires precision control of both flight path and airspeed. Finally, it is becoming more and more common to use modified civil aircraft in either the military transport or in-flight refuelling roles, with the Vickers VC-10 and Lockheed L-1101 being used as in-flight refuelling receivers and tankers and the Nimrod (Military Comet) as a receiver in the Royal Air Force alone.

It was also decided to consider atmospheric effects. Initially, it was proposed to consider the effects of both windshear and turbulence, but evaluations in turbulent conditions were later dropped since its main effect is in the longitudinal (airspeed) axis, with effects in the longitudinal (pitch) axis being limited by the effects of the control laws. However windshear, which here is taken to represent a decreasing headwind, is a flight path control problem (see section 8.1) since it causes an effective change in aircraft flight path angle, and it was found to be a much more suitable task.

1.6 Control Laws Under Consideration

For this evaluation ten different control laws were considered plus the baseline aircraft. The control laws are based on laws in current use, or derivatives of them, and have been designed to a series of law-independent requirements. Effects due to changes in the position of the aircraft centre of gravity have been ignored for these evaluations. Since the control laws can be designed to cope with this in a way which is transparent to the pilot. Changes in aircraft mass have been ignored for the same reasons. Lateral and directional control laws have not been explicitly considered. The reason for this is that the majority of fly-by-wire aircraft utilise the same lateral control law strategy, and this has been adopted for this aircraft. An existing lateral law for the aircraft under question was therefore used.

1.7 The Objectives of this Work

The thesis is designed to consider the flying qualities of the current fly-by-wire transport aircraft, and to look at the associated project management issues.

1. To further the work of Field, whose work precedes this;
2. To produce a set of flying qualities design requirements for transport aircraft primarily for the approach and landing task;
3. To consider the project management implications of fly-by-wire technology;
4. To consider alternative tasks to the Instrument Landing System task normally used for flying qualities assessment;
5. To consider the suitability of the current flying qualities requirements for transport aircraft.

1.8 The Structure of this Thesis

This thesis is structured in the following way:

Chapter 1 introduces the work.

Chapter 2 contains the management Chapter, which details the project management issues associated with an advanced technology aircraft.

Chapter 3 contains a description of a classical aircraft response, plus a description of the different types of aircraft response characteristic.

Chapter 4 contains a description of the current flying qualities criteria, plus analysis of a number of different configurations against these criteria.

Chapter 5 contains a brief description of a number of past flying qualities research programmes, including analysis of these programmes against modern flying qualities criteria.

Chapter 6 contains a description of flight control system design requirements for a medium sized transport aircraft, plus a description of how to design a fly-by-wire flight control system for that aircraft.

Chapter 7 contains a brief description of a flying qualities experiment designed to look at flying qualities for a number of different control laws for a generic regional aircraft.

Chapter 8 describes a further set of flying qualities evaluations looking at the generic regional aircraft in the formation flying task and approach and windshear task.

Chapter 9 contains a summary discussion of the results of this work.

Chapter 10 concludes the work.

Appendix A contains additional information concerning the project management work.

Appendix B contains some of the results of an extended investigation into past flying qualities programmes.

Appendix C contains some of the results from the reconfiguration and ILS approach tasks.

Appendix D contains some of the results from the windshear approach and formation flying tasks.

2 Project Management Tools for Aircraft Design

This Chapter considers the project management implications of the flight control system design process. A brief study is made of the current project management tools and methodologies in current use before several aerospace design case studies are described. These illustrate the use of modern project management tools and techniques. Finally, a process model is derived for the generic regional aircraft under consideration and improvements and benefits that the project management tools could bring are suggested.

This Chapter assumes that the reader has a reasonable level of general knowledge concerning the basic process required to design and build an aircraft, but little knowledge of specific project management tools or methodologies. It is intended more as a guide to these project management tools and the type of benefits that they may bring as opposed to a handbook into how to build an aircraft! This decision was made as every company may do things slightly differently, and therefore the benefits that individual project management tools may bring to them will depend on their processes and their 'way of thinking.' Minor differences in the process model may exist and are acceptable with this in mind.

2.1 Introduction

During the last 50 years, the cost of systems has been driven by improving performance to ever increasing levels, even after inflation has been removed [7]. Therefore, to quote Augustine [8], 'in the year 2054, the entire defence budget will purchase just one aircraft. This aircraft will have to be shared by the Air Force and Navy for 3 1/2 days each per week, except for the leap year, when it will be made available to the marines for the extra day.' We have been obtaining more performance per dollar. However, the overall cost has risen exponentially. Therefore there is a need to design for cost and maybe to the minimum required performance level.

The loss of the Ariane 5 highlighted several important considerations in systems design [9]. Firstly, validation of requirements is important. Individual requirements must be traceable throughout the system. The Ariane 5 failure was caused by errors in the specification and design errors in the Inertial Reference System, which had been successfully used on Ariane 4. The assumption was made that the system would work on the Ariane 5, but this was not the case.

System complexity is estimated to be increasing at an enormous rate, of the order of 20 % per year [10]. Space Station Freedom will have over 1.5 million requirements over which traceability is required. Such complexity, coupled with ever increasing safety and reliability requirements means that design and traceability can no longer be handled by traditional methods.

In addition to the increase in individual systems complexity, the interaction between systems is also increasing at a great rate [11]. In the Boeing 707 there was little interaction between systems, i.e., individual aircraft systems operated more or less autonomously, and with little need for interfacing between them. However, this is no longer the case with the more modern Boeing 767 and an even higher degree of coordination and computation is required on the Boeing 777. In order to accomplish this, a much larger and more specialised workforce has evolved, and it is also the case that a few talented people can no longer keep track of the design. A more structured approach is therefore needed.

This Chapter addresses the use of project management techniques in the aircraft design process. Specifically, the relationship with respect to the flight control system is addressed. The initial sections may also be used as a reference to project management tools and also examples from several aerospace companies who have used some of the more modern project management tools in aircraft design are given.

2.2 Project Management Tools commonly used in Aerospace projects

This section describes the common project management tools currently in use.

2.2.1 Sequential Engineering

A traditional method for engineering a product may be as follows. The Marketing department identifies the need for new products, price ranges, and the expected performance from (potential) customers. Design and engineering receive loose specifications, and commonly work alone in developing the technical requirements and the final detail design and documentation.

Since the design is carried out in relative isolation, manufacturing, test, quality and service functions only see the design in its completed state. This is known as sequential engineering since the process is sequential in progression, as each stage of product development follows completion of the previous stage [12]. This is also commonly known as 'over the wall engineering' since departments receive as much warning or involvement on previous stages as if the product had been thrown over the wall.

There are many weaknesses of this approach [12] which may give the following problems:

- There is insufficient product specification leading to an excessive number of modifications due to the lack of involvement and cooperation between functions;
- There is little attention to manufacturability issues of the product at the design stage;
- The estimated costings are usually orders of magnitude in error, due to mainly uncontrolled late design change costs. This leads to a lack of confidence in the estimated costs of projects;
- Late changes usually lead to expensive changes to tooling and other equipment.

Requirement specification is important [13]. Well defined, and timely requirements, objectives and goals for the system or product under development have been recognised by successful, highly competitive companies as a critical success factor in time to market. They have now recognised this element of the development process as a key activity in their time to market cycle time. Disciplined approaches such as Quality Function Deployment (QFD) are becoming important tools in the systems engineering process for both commercial and military systems. These tools will be described later.

2.2.2 Simultaneous Engineering

The use of innovation to achieve a competitive edge is not new [14]. What is of current interest is how some manufacturing organisations have used the speed of product innovation to gain a competitive edge. To do this, many firms have applied the technique of simultaneous engineering. The most common subject of previously published work on simultaneous engineering has been applied to product innovation.

According to Sweeney [14], Rolls Royce define simultaneous engineering by stating

> Simultaneous engineering attempts to optimise the design of the product and manufacturing process to achieve reduced lead times and improved quality and cost by the integration of design and manufacturing activities and by maximising parallelism in working practices.

Vital elements of simultaneous engineering include:

- A multi-disciplinary task force or design team;
- Product definition in a customer's terms and then translated into engineering terms in considerable detail;
- Parameter design to ensure that the product is optimised for use and quality through the use of Quality Function Deployment (QFD), see section 2.2.6;
- design for manufacture and assembly;
- simultaneous development of the product, the manufacturing equipment and processes, quality control and marketing known as Design for Manufacture and Assembly (DFMA).

The use of QFD and DFMA are vital for an appropriate definition of the product concept. In addition, QFD helps to ensure that a competitive edge is established [14].

2.2.3 Systems Engineering

Systems engineering is fundamentally a methodology for the systematic approach to the specification, design, development and validation of any system [11]. Systematic means that all participants follow the same orderly process, and there is design traceability from the top level to the lowest level.

According to Blanchard [15], system engineering can be broadly defined as 'the effective application of science and engineering effort to transform an operational need into a defined system configuration, i.e. the top-down iterative process of requirements definition, functional analysis, synthesis, optimisation, design, test and evaluation.'

MIL-STD-499A also defines system engineering and is considered later. Systems engineering has been recognised as the process by which the orderly evolution of man-made systems can be achieved [16]. It has been written that the system idea, i.e. the solution of a complete problem in its full environment by systematic assembly and matching of parts to solve the whole problem in the context of the lifetime use of the system and considering all aspects is one of the most important ideas of modern times. It has made possible the solution of complicated problems that previously could not be touched.

In addition, another definition mentioned in [16] defines systems engineering as

> An iterative process of top-down synthesis, development and operation of a real world system that satisfies, in a near-optimal manner, the full range of requirements for the system.

According to Alford [10], systems engineering is unique in two main respects: it is perhaps the only multi-disciplinary engineering discipline, and it emphasises "design by allocation", an approach which is not usually found in other engineering disciplines. Other key issues to maximise development effectiveness are [13]

1. The need to examine the functional composition of the core team; in particular to maximise the individual members' systems approach to their allocated and assigned functions, depending upon system functionality requirements.

2. The need to strengthen the systems engineering process and technical knowledge skills of the core team accountable for the development undertaken.

3. The need to create system sensitivity awareness similar to the concept of 'risk awareness,' a critical component of effective risk management programs.

Systems engineering is defined by Petersen [11] as ' a systematic approach to the engineering of a total system.' A systematic approach in the context of aircraft design considers the **process** of:

1. defining airplane top level system requirements;

2. the synthesis of the system architecture;

3. the allocation of requirements to each element in the system architecture;

4. the definition of the detailed system requirements down to the lowest level;

5. the validation of the requirements (making sure that they are the **right** requirements;

6. the definition (detailed design) of the system elements;

7. the manufacture of the elements;

8. the verification and validation of the designs as manufactured (singly, at subsystem level and finally at system level);

9. and finally, product delivery.

A major effort of systems engineering is the allocation of the customer's performance specifications to the system and subsystem level of the contract [17]. This is consistent with TQM (see section 2.2.5), and is also the first stage of QFD (see section 2.2.6).

MIL-STD-499

This military standard [18] is an ideal source for preparing a process [16]. It was initially developed to assist the US government and contractors in defining a single standard in the systems engineering effort in support of procurement. It contains the essentials in how to perform engineering management in an orderly manner. The basic message proposed by this standard is that the program manager has to plan ahead to minimise the unexpected and to know what is going on at all times. MIL-STD-499A is a top level document and contains reference to other standards and specifications.

MIL-STD-499A defines system engineering as a logical sequence of activities and decisions transforming an operational need into a description of system performance parameters and a preferred system configuration, although according to Kasser [16] this tends to indicate that the systems engineering process finishes when the analysis phase is complete.

MIL-STD-499A makes reference to the following requirements [16]:

- *Technical objectives* - these must be established so that goals may also be established, and meaningful relationships between risk, work, need and urgency may be formulated in order to establish priorities;

- *Realistic system values* - MIL-STD-499A calls for realistic values for reliability, maintainability and other parameters prior to development;

- *Design issues* - MIL-STD-499A calls for the design to be simple, using as many standard parts as necessary. The design shall also be complete as a total system. i.e. the system should do what it is supposed to, and not do what it is not supposed to;

- *Documentation* - MIL-STD-499A calls for minimum, but adequate documentation. Engineering data is the sole source of performance requirements to be used. The data and document archive facilities must also be specified. Design changes must always be documented;

- *Miscellaneous* - Other issues to be considered are baselines, technology issues, cost estimates, the work breakdown structure, engineering integration, design process archiving, historical data and responsiveness to change.

MIL-STD-499A has undergone several revisions since its first issue, and this has matured into MIL-STD-499B. Some of the changes which have appeared are as follows [16].

- *The concurrent engineering approach* - this standard now requires a structured, disciplined and documented systems engineering effort to be established, including multidisciplinary teamwork and simultaneous product and process development needed to satisfy user needs.
- *The iterative systems engineering process* - requirements analysis shall be conducted iteratively with functional analysis to develop requirements, and verify that people, product and process solutions can satisfy the customer requirements.
- *Measurement of progress* - the performing activity shall implement the systems engineering master schedules for top-level process control and progress measurement.
- *Controlling changes* - the performing activity shall define the total program impact of specified change to technical requirements with respect to cost, schedule, performance and risk.
- *Cost effectiveness* - system cost effectiveness analysis and assessment shall be used to support development of life cycle balanced products and processes.
- *Models* - models shall be used whenever they contribute to the decision process. The effect of individual parameter effects on system performance and life cycle costs shall be determined. Requirements are placed on the models, their documentation and the validity of the data within the models.
- *Tailoring guidance* - in each application, the standard should be tailored to the specific program requirements. Any factors which do not add value to the process or phase should be eliminated.
- *Glossary* - many new terms have been added in the glossary.
- *Primary system functions* - The eight essential tasks that ensure the system will satisfy the customer needs from a system life cycle perspective are development, manufacturing, verification, deployment, operations, support, training and disposal.

Systems Engineering Phases

The "design by allocation" concept is used by systems engineers to divide the overall system definition job into several actions:

1. The customer requirements are reviewed and understood;
2. The black box functionality and performance of the system is defined without regard to how it might be distributed between components;

3. The systems functions and performance are further decomposed and allocated to functions- this allocation is not unique, so many different allocations may be explored while preserving the agreed-to black box system behaviour;

4. The black box behaviour allocated to the component is reviewed by the component designer and assessed for cost, schedule, risk, technology limits, and recommendations for alternative allocations which might provide advantages; the design and allocation is also reviewed by engineering specialities;

5. The analyses from multiple designs are subjected to trade-off analyses in order to select the design which best satisfies the overall project goals. The design is published after the final segmentation has been decided so that the component developers can start their design process. Traceability of the customer requirements to this design is also published to ensure that the customer requirements are also met;

6. Finally, the systems engineers then monitor the design for conformance to the intended allocation of functions and performance, and required changes are processed to give specification changes.

In addition, documentation forms an important part of the above process and is updated as required and as work progresses. The actions listed above are generally split into 5 phases defined by NASA in reference [19] and they are described below.

Phase A (Conceptual Trade Studies)

Trade studies are a qualitative and/or quantitative comparison of candidate concepts against key evaluation criteria to determine the best alternative. Trade studies provide a mechanism for systematic depiction of both system requirements and system design options for achieving those requirements. Once tabulated, a comparison of relevant data is performed to rank those candidate design options in order of desirability.

A trade tree may be used to perform this study. A trade tree is a pictorial representation of how high level alternatives (or issues) may filter down into low level alternatives (or issues). A trade tree may be presented as a representation of options.

A weighted factor trade study is usually performed when each of the options under consideration is well defined and there is a good definition of program requirements. All factors that are deemed to be important are delineated with an associated weighting factor. These weights are then used to assess the different options, and a decision is then based on the results of these evaluations. The scores may be linear or non-linear, as required, and their relation to specific performance criteria should be determined before the different options are evaluated.

Therefore the evaluation and weights need to be performed from the perspective of the operator. It is likely that he will not be interested in specific solutions to the problems, but he will be interested in the problems themselves, and the importance of each.

Different kinds of study allow flexibility in the depth of the review, i.e. resources expanded can be varied to the level of detail required. The studies can be expanded to be based on programmatic or schedule considerations as well as technical ones. However the study is dependent on the expertise of the analyst and on the availability of the required data. In addition, the determination of inappropriate selection criteria can prejudice the assessment and lead to inappropriate results.

The options to be evaluated are determined prior to the studies, and not as a result of the studies. Finally, the results can be very subjective, and this may influence the results. Therefore care must be taken to ensure that the results are objective.

Cost benefit studies can be used to assess the cost of the project during the entire lift cycle of the proposed system. In addition, it provides documentation of the parameters evaluated and the prioritised options considered. Again, this analysis is flawed if the system requirements are incomplete or inaccurate, and the operating environment is not fully understood. Then it can lead to misleading information. Also, if the system requirements are too general or vague, then the effectiveness of benefits can not be addressed in specific measurable terms.

Phase B (Conceptual Definition)

The establishment of system design requirements as well as conceptually designing a mission, conduct of feasibility studies and design trade-off studies.

Trade studies or cost benefit studies may also be performed during this phase. The cost benefit analysis is only as good as the list of alternatives considered. An incomplete list of alternatives will lead to an incomplete analysis. Finally, the analysis must be able to quantify the benefits which are often intangible or insubstantial and difficult to characterise in terms of value.

A preliminary hazard assessment may be performed during this phase.

Phase C (Design and Development)

The initiation of product development and the establishment of system specifications. Most of the design analysis and work is carried out during this phase. Cost benefit studies may also be performed during this phase.

A risk assessment matrix will probably be performed during this phase, although it may also have been performed during phase A. A preliminary hazard assessment will typically be performed during this phase, although it may also have been performed during phase B.

A preliminary hazard assessment will typically be performed during this phase. This is used to identify the people, objects, etc. which need to be protected. The levels of risk then need to be identified, either by the operator or the regulatory body. The risk may need to be defined for specific operating phases. There may also be warning device and training considerations.

Failure modes and effects analysis are typically performed during this phase. This is a bottom-up technique which explores the ways or modes in which each system element may fail. They are a useful tool for cost and benefit studies, and to implement risk mitigation and management, and as a precursor to fault tree analysis. This technique allows single point failures to be determined. This is typically performed during phase C.

A reliability block diagram assessment may be performed during phase C. This is a top-down symbolic logic model generated in the success domain. Combinations of components may be combined, plus their reliabilities to provide an overall system reliability. Simple or complex systems may be considered. In addition, there is a limited capability for determining the system reliability where the reliabilities of individual components lie within specified bands.

Fault tree analysis is a top-down symbolic logic model generated in the failure domain. It works by generating a failure event, and then analysing which low level components could cause this failure. It is a useful technique for systems where there are potentially high severity events.

A success tree analysis is similar to a fault tree analysis, except that it considers success as opposed to failure.

Phase D (Fabrication, Integration, Test and Evaluation)

This phase considers fabricating and testing the product. Most of the analysis work carried out looks at production issues with the product which consider achieving quality in production. Statistical analysis may be carried out to look for problems and to achieve this desired quality. In additional, some initial fault analysis with the product may be carried out using tools such as fault tree analysis, cause-consequence analysis and failure mode information propagation modelling, although this analysis is secondary to the primary tasks within this phase which are to produce the product. These tools are described further in reference [19].

Phase E (Operations)

The principal activities within this phase consist of operating the product, and cause-consequence analysis and event tree analysis. The development of the product and performance validation must also be considered.

This is also the time that the customer may be consulted to ensure that the product is achieving their specifications, and in the case of an aircraft, this may require the aircraft to be operated in service for a period of time before this may be ascertained.

In the case of a complex product such as an aircraft, there may be time allocated in the initial period for in-service modifications to be made as a result of either the latter stages of testing, which are likely to be carried out while the aircraft is being operated in service, and also as a result of the initial customer findings. Testing may continue for a little while after the product has entered service in the case of an aircraft since the latter testing will confirm both the safety of the aircraft, and also the in-service reliability and maintainability.

The System Life Cycle

According to Chapman, Bahill and Wymore [20] the system design process has seven distinct phases. These are listed below, and are essentially similar to the NASA design phases.

1. Requirements development;
2. Concept development;
3. Full scale engineering design and development;
4. Manufacturing and deployment;
5. System integration and test;
6. Operation, maintenance and modification;
7. Retirement, disposal and replacement.

Product and process complexity are blurring the distinctions between the design tasks in the individual engineering domains [21]. In addition, the requirement for the product to perform as a technical design, as well as a cost effective, timely and high quality system over an entire cycle life is increasingly demanded by customers. In an increasingly innovative and competitive market, two interrelated and dependent factors now demand success - customer and stakeholder (i.e. anybody not a customer) satisfaction.

Systems engineering is defined by Wetzer [21] as ‘providing suppliers and customers of complex products and systems with a formalised method to effectively manage a product’s conceptual requirements determination process through to its disposal requirements- optimised for greatest beneficial utility, schedule, cost and quality.’ This definition states that it is more than a tool; it provides a practical approach to balance all needs attendant to the satisfactory operation and beneficial use of a product or system over its life time.

Automation of Systems Engineering

According to Alford [10], system engineering needs cannot be satisfied without significant automation with specific characteristics.

Systems engineering is generally performed with pencil and paper, and non-specific tools, such as spreadsheets and word processors [10]. With the exception of Personal Computers, this is similar to the way in which things were done 20 to 30 years ago. This is contrasted to the Computer Aided Design (CAD) and Computer Aided Engineering (CAE) tools which have evolved to support the specification and design of components. The use of these unconnected tools solves some problems, but can create more and they may not address other problems. For example, consistency in the design is important, whether it is between documents, designs or specifications.

Automation has several issues involved, and these are listed below [10]:

1. Increased productivity due to increased quality. The primary use of automation is to increase the consistency and completeness of the system description, and thus reducing the cost of repairing latent defects when discovered later in the process. Automation systems can go a long way to finding inconsistencies at system specification time, and therefore reduce the cost of fixing the problem later down the line, where it is invariably many more times as expensive to make modifications;

2. Increased productivity during maintenance and modifications. Since the design is traceable to individual customer requirements, the impact in the change in customer requirements is readily traceable. Again, changes required to the documentation can be made since the document generation process is formalised, and changes in the engineering design can then be immediately reflected in the documentation;

3. Automation of day to day activities. Increased performance for the people involved due to:

    (a) A decrease in the amount of time required for review documentation generation;

    (b) Automated consistency checking;

    (c) Design decision capturing and traceability;

    (d) System modelling and analysis;

    (e) Efforts of eliminating ambiguity.

4. Reduced development time. Development time should be reduced due to enhanced communication between individual team members. In addition, time is saved due to the fact that the documentation is on-line and accessible, and can be reviewed continuously;

5. Smooth transition to downstream methods and tools. This saves text being manually re-entered, which is the usual way for a design to progress downstream. This saves duplication in effort, and inconsistencies, especially if the specifications can be translated directly into the low level design.

2.2.4 Quality

Quality is an important concern for all business organisations. It is defined in reference [22] as follows:

- Quality is the ability to meet market and customer expectations, needs and requirements;
- Quality is suppyling goods that do not come back to customers who do;
- Quality means in conformance with user requirements;
- Quality means fitness for use.

Smith [22] defines quality as the ability to manage a project and provide the product or service in conformance with the user requirements on time and to budget, and where possible maximising profits.

Currently, most business organisations now require a potential partner, supplier or vendor to operate a quality system, and businesses which do not are now loosing custom. The British quality assurance standard BS 5750 and the International Standards Organisation standard ISO 9000 series are internationally recognised standards which demonstrate a specified quality system.

A quality system should incorporate all stages of product design and development from conception to operation, and sometimes through to decommissioning. Quality and cost requirements may be defined during the early design stages. In order to achieve the desired quality without unnecessary costs, an efficient system of coordinating the project's activities must be found. The quality system should ensure that:

- The quality products and services should always meet the expressed or implied requirements of the customer;

- The company manager knows that quality is achieved in a systematic way;
- The customer feels confident about the quality of goods or services supplied and the method by which they are achieved.

Finally, the quality system must be adjusted to suit the project's operation and the final product. It must be designed so that emphasis is put on preventive actions, at the same time allowing the project manager to correct any mistakes that do occur during the project life-cycle.

ISO 9000

Quality control is evolving from only being present during the final evaluation to becoming an integral part of the entire process. This evolution is being helped by the ISO 9000 series of standards, which provide a checklist for documenting processes and assessing their performance [16]. ISO 9000 was developed because customer specifications are often incorporated in "specifications." However, the specifications may not in themselves guarantee that a customers requirements will be met consistently, if there are any deficiencies the organisational system to supply and support the product [16]. At present, the standards do not apply to systems engineering, but this is likely to change soon.

The International Standards Organisation initially developed the 9000 series quality system standard in 1987, and subsequently published revised standards in 1994. There are five basic standards:

- ISO 9000 - quality management and quality assurance guidelines. It explains the philosophy behind the standards and provides a road map for their application;
- ISO 9001 - model for quality assurance in design and development, production, installation and servicing. It is applicable where a contract specifies a design effort and the product requirements are stated in performance terms or need to be established;
- ISO 9002 - model for quality assurance in production and installation. It is applicable when the product requirements are stated in terms of an established design or specification;
- ISO 9003 - model for quality assurance in final inspection and test. These demonstrate that the product meets specifications through the supplier demonstrating that his test procedures meet the standard;
- ISO 9004 - quality management and quality system elements. This provides guidance on how to implement a quality program within a company.

A more detailed description is given within reference [16].

Cost of Quality

The cost of quality is considered to be the primary quality measurement tool [23]. It is often used to track the effectiveness of the TQM process, to select quality improvement projects and to provide cost justification to anyone doubting the TQM process. By bringing together a collection of saved costs, one can easily demonstrate an accumulation of expenses to convince management and others of the need for TQM.

Quality costs can be further broken down, although these costs are 'saved' costs as opposed to expenditure.

$$Quality\ Costs = Control\ Costs + Failure\ Costs \tag{2.1}$$

$$Control\ Costs = Prevention\ Costs + Appraisal\ Costs \tag{2.2}$$

$$Failure\ Costs = Internal\ Failure\ Costs + External\ Failure\ Costs \tag{2.3}$$

Prevention costs are costs incurred as a result of quality activities to avoid deviations. Appraisal costs are costs incurred to determine whether a product, service etc. conforms to established requirements. Failure costs are costs as a result of not meeting the requirements. In addition, the improvement in productivity that TQM brings through employee satisfaction may be quantified.

2.2.5 Total Quality Management

According to Oberlender [23], much of the attention which has been paid to Total Quality Management (TQM) has been due to its success in its application in the manufacturing and electronics industry, particularly in Japan, where the TQM concept started in the early 1950s. The TQM philosophy concentrates on process improvement, customer and supplier involvement, teamwork, and training to achieve customer satisfaction, cost effectiveness and defect-free quality work.

According to Blanchard [15], quality has been viewed more from a top-down life cycle perspective, and the concept of TQM has evolved from this. He defines TQM as 'a total integrated management approach that addresses system/product quality during all phases of the life cycle and at each level in the overall system hierarchy.'

In addition, it focuses on system design and development activities, as well as production, manufacturing, assembly, construction, product support and related functions. It links human capabilities to engineering, production and support processes. Joseph Bellefeuille stated in the Engineering Management newsletter of July 1993 [24]:

> Total Quality Management is an interlocking arrangement of procedures and practices ensures that ALL EMPLOYEES in every department are adequately trained and directed to CONTINUOUSLY IMPLEMENT CONGRUENT IMPROVEMENTS IN QUALITY, SERVICE AND TOTAL COST such that CUSTOMER EXPECTATIONS are met or exceeded.

TQM may also be implemented under a concurrent project management framework [24]. According to Kasser [16], TQM is the application of systems engineering to the work environment. Many of the TQM tools are identical to the systems engineering tools, but with different names.

TQM management philosophy focuses on continually improving the process that makes the product, rather than attempting to test or assess the product to achieve quality. The approach uses statistics to control the process: where management's role is not to solve all of the systems problems, but to provide workers with the tools that are necessary for them to effectively address the problems in the system.

Much of the TQM concept is due to the 'teachings' of Drs W Edward Deming and Joseph M. Juran, who, with other experts from the USA assisted the Japanese in improving the quality of their product beginning in the early 1950s. Deming emphasised that the majority of the problems encountered in manufacture are with the process, and statistics can be used to control the process (see Statistical Process Control, section 2.2.7). Juran outlined a managerial approach to quality control and focused on achieving customer satisfaction through a project team approach with project-by-project improvement. He emphasised training at all levels, from workers to top management, with the emphasis being placed on continual improvement.

In 1986, Deming published a book entitled 'Out of the crisis' which defines the following 14 points or steps which must be considered. These steps are stated below:

1. *Create consistency of purpose for improvement of product and services.* This includes both immediate solutions to today's problems and long range planning for the future;

2. *Adopt the new philosophy.* The change is not only to the management and workforce of the company, but encompasses the responsibilities of the government as well;

3. *Cease dependence on mass inspection to achieve quality.* The problem is not with the defective products found during inspection, but in the system which created them;

4. *End the practice of awarding business on the basis of price tag alone.* Instead minimise cost by working with a single supplier;

5. *Improve constantly and forever the system of production and service.* Quality must built in at the design stage;

6. *Institute training on the job.* Ensure everyone understands their job and has training to do it;

7. *Adopt and institute leadership.* The job of management is not supervision, but leadership;

8. *Drive out fear.* People do their best work when they feel secure. Encourage contributions from everyone to improve the system;

9. *Break down barriers between staff areas.* Instead of optimising the efforts of individual departments, the effort should be made to develop a team approach for the good of the company;

10. *Eliminate slogans, exhortations and targets for the work force.* Such devices cultivate resentment when there are flaws in the system hampering optimum performance;

11. *Eliminate numerical quotas for the work force and numerical goals for the management.* Quotas either breed a sense of failure when they are not met, or stifle incentive if they are met too easily;

12. *Remove barriers that rob people of pride of workmanship.* Eliminate the annual rating or merit system;

13. *Institute a vigorous program of education and self-improvement for everyone.* Allow people to improve themselves and broaden their knowledge with continuing education;

14. *Take action to accomplish the transformation.* The best plans for improving the system are worthless unless they are put into action.

TQM must be tailored to the specific needs of a company, and cannot be simply adopted from a consultancy and implemented. It requires the action, involvement and commitment of senior management, and through the use of a pilot program, it can take approximately three years before it is accepted throughout a company and significant results are achieved.

According to Oberlender [23], customer satisfaction and continuous improvement are the fundamental goals of TQM, and therefore the principles upon which it is based. TQM is a management philosophy which effectively determines the needs of the client and provides the framework, environment and culture for meeting them at the lowest possible cost.

Customers may be internal or external. External customers are not part of the company producing the product or service, whereas internal customers are customers within the firm / organisation. These internal customers receive products or information from others within the organisation. In addition, every party has three roles according to Juran, and he defines this as the triple role concept. The three roles (supplier, processor and customer) are carried out at every level of the process.

To achieve TQM, management has two functions [23]. The first is to maintain and incrementally improve current methods and procedures through process control. The second is to direct the efforts necessary to achieve major technological advances in engineering and construction processes through innovation.

According to Smith [22], there are four main elements to TQM. Each is required for the TQM process to succeed. The four elements are:

1. Management commitment;
2. Teamwork;
3. Techniques;
4. The quality system.

Some of the advantages of TQM include reduction in costs due to reducing the costs due to poor quality, the money saved through meeting the specification, and the benefits due to the system, such as providing a basis for teamwork and interaction techniques, recognising the need to balance risk, benefit and cost, and finally the system allows and documents changes in the project.

The concept of continually improving processes is one of the fundamental ideas behind TQM. The ability to produce a quality product largely depends on the relationships between the supplier, customer and producer. The quality of any process downstream is strongly dependent on the quality of the upstream processes. Close and long term relationships with the supplier are required if the company is going to achieve the best economy and quality.

Total Quality Management was mandated in 1988 by the US DoD to improve the quality of contracted systems to reduce costs and inefficiencies, and to develop an efficient industrial base for future programs [17]. TQM has focused on increasing the quality and reliability of products and equipment, while removing the non-value added costs.

The systems engineering management process is critical to every program, and in this role is in the prime position to initiate and participate in the TQM process improvement [17].

TQM is the guidance needed to review all of our systems, personnel and methodologies of management to improve the process of systems engineering [17], the process of engineering design and the process of manufacturing.

2.2.6 Quality Function Deployment

Quality Function Deployment is a technique that originated in 1972 at Mitsubishi's Kobe shipyard site [16]. It reduced preproduction costs at Toyota Autobody by more than 60 % between 1977 and 1984. Dean states [25]:

> QFD uses a basic dimensionality within a project to provide a structured way of designing quality into a system. It addresses dimensions including customer desire, quality characteristics, functions, parts and failure modes.

Some of QFDs strengths are

- It is effective at capturing, communicating and understanding the customer's requirements;
- It is a structured methodology to increase the probability that products will be designed to reflect customers desires and tastes;
- It facilitates teamwork and a concurrent engineering approach by requiring staff from different functions to work together;
- It makes the customer think about the real need for each requirement.

From this, the following benefits may be realised [12]:

- Reduced product development cycle time;
- Improved customer satisfaction;

- Increased competitiveness.

QFD is a structured planning tool which can be used to influence the incorporation of product attributes which are in accord with customer expectations. It is performed by mapping the customer requirements into specific design features (and eventually into manufacturing processes). It is used as a systematic approach to both identify and prioritise customer requirements, and to translate these requirements into product and process specifications [12].

According to Syan [12], it is logical to think of the QFD approach as somewhat similar to the systems engineering approach. However, QFD is superior to systems engineering since it QFD places an emphasis on understanding the interrelationships among the requirements at the various levels of design. Thus QFD captures a great deal of the design information which is lost in the systems engineering approach. Other differences are [12]:

- QFD emphasis not only the product, but also the production process while systems engineering focuses on the product;
- QFD reflects the 'voice of the customer' since the original customer requirements dictate the design activity. In contrast, the system engineering generated 'requirements specification' are considered to be the voice of the engineer, as the engineer generally takes responsibility for the requirements with systems engineering;
- QFD provides a way to reconcile conflicting elements, whereas systems engineering cannot do this.

Systems engineers use QFD to translate customer requirements into technical requirements for each stage of product development.

According to NASA [19], Quality Function Deployment (QFD) is used to solve problems before the production phase begins, and this assists in the design of competitive products. By using a 'house of quality', priorities are given to the possible solutions as they relate to the identified problems. Also, the product can be benchmarked against the competition in the areas of how well the product compares against the competition as far as identifying the identified problems, and how well the product stacks up against the competition as far as meeting the appropriate engineering standards.

QFD helps organisations to design more competitive, higher-quality, lower-cost products easier and quicker, and helps to ensure quality through detecting and solving problems early. It is also a cost-effective technique which helps to prevent engineering changes and reduces design cycle and start-up costs. However, even though this technique is easy to learn, it is not easy to perform, and it can be time-consuming.

QFD is a way of turning WHATs (customer concerns) into HOWs (quantifiable solutions to the concerns). The name 'house' came about through the matrix which is used to perform the analysis. Techniques such as brainstorming are used to assist with the creation of the matrix.

QFD is often performed in system engineering phase C, but may also be performed in phase A or B. This technique may be used by every function in the organisation, and at every stage of design. It also enables a prioritisation of the HOWs as it helps with the identification of a 'best solution' through the quantification of overall rating of the proposed solutions. These ratings indicate which solutions are most important and need to be considered first. According to NASA [19], the most important reason for using QFD is identify the problem areas first and propose quantifiable solutions to these problems early in the design phase so these issues will not have to be faced during production, which could lead to delays and higher costs.

Quality function deployment could have been used to great effect in the Ariane 5 incident [9]. The fault in the launcher which caused the accident was caused by software running which was not even needed. The application of QFD to the system would have shown this, and the accident may never have happened.

2.2.7 Statistical Process Control

According to NASA [19], Statistical Process Control (SPC) is a process improvement tool which helps identify problems quickly and accurately. SPC is used to determine the cause of variation based on a statistical analysis of the problem. It helps with process performance, and helps to identify problems quickly and accurately. However, it is only detects the problems, and does not pose solutions.

Historical data of the performance of the process (or the operation of hardware) is statistically analysed to predict future performance or to determine if a process is in control. A process is defined as being 'in control' if there are only random sources of variation present in the process and associated data. SPC can cope with processes which are both in control and not in control.

SPC is best performed in systems engineering phase E. This process is used to determine if special causes of variation are present in a process, or if all variation is random. In other words, SPC is used to ensure that a product is being produced consistently, or is about to become inconsistent. Therefore SPC can be used to identify problems in a system before defective hardware is delivered.

Trend analysis tools are used to identify potentially hazardous conditions and cost savings based on past empirical data. This type of analysis can be used to determine whether a product may be left in service for longer than initially envisaged, or to determine whether some hardware inspections need to be eliminated. It is performed through measuring parameters which may impact personnel safety, system performance, the delivery schedule, the manufacturing cost etc. Trends may be analysed to determine where changes may be required.

2.2.8 Designing for Cost

Designing for cost is different to designing to cost [11]. Designing for cost is the orientation of the engineering process to reduce life cycle cost, whilst satisfying, and hopefully exceeding customer demands. Design for cost is also the conscious use of engineering process technology to reduce life cycle cost. Design to cost is the iterative redesign of a project until the contents of the project meet a given budget, therefore performance is reduced until the budget is met. Design for cost seeks to reduce costs as far as possible while meeting customer demands.

2.2.9 Risk Management

According to Vlay [26], the need for risk management to accomplish the program successfully is even greater as the demand to reduce development cycle time is stronger. Risk management is therefore required to prevent major problems occurring when it is too late to fix them.

Lack of risk management can produce products which are late to the marketplace or products which have less than optimum performance [26], which can provide negative articles and reports in the press and trade journals. In addition, products with these attributes often have had unrealistic time constraints imposed on them, a lack of management attention, and a lack of technical skills.

As the programmes become more complex, the interactions and interfaces become much more complex, and require additional time for rework and test [26]. This means that many more companies experience problems in developing upgrades to their existing products or to meet a business or market schedule. The market may drive the schedule, but the program complexities will drive the risk, and in turn establish the final deliverable schedule.

According to Vlay [27], the major element which has been missing in the program management responsibility has been the integration of risk management. Without this risk management, it can become too late in the program to implement solutions to problems, and therefore costly.

Risk management is an extension to good program management and systems engineering procedures and tools [27]. It emphasises the need to identify problems as early as possible because of the increasing potential technical, schedule and cost impacts as time progresses.

Risk management can be used from the initial aircraft conception. Anderson et al [28] propose a method whereby the risk associated with the flight control system is calculated through a series of parameters calculated from the conceptual aircraft design. This method allows the system risk to be computed based on a simple conceptual design, and past experience, and therefore the risk associated with the often complex flight control system can be calculated. However, these methods require a certain amount of data to be collected on past programmes before they can be initiated.

2.2.10 Concurrent Engineering

According to Dean [25], concurrent engineering is a natural part of the QFD process for large systems. This is because expertise across many fields is required to define and rank the customer demands, functions, quality characteristics, systems, new concepts, failure modes and the associated correlations.

According to Turtle [24], concurrent engineering embodies:

- Product design as driven by manufacturing requirements;
- Design for manufacture and quality engineering specification of test procedures and testability of design features;
- Team building and goal concurrence from all team members.

He then states that concurrent project management is a step further than this. Concurrent project management includes everything within concurrent engineering, plus marketing, finance, purchasing, human resources, engineering and manufacturing, all in the same team-building process and all achieving concurrence as a team.

According to Blanchard [15], concurrent engineering is intended to cause the developer, from the outset, to consider all elements of the product life cycle, from conception through disposal, including quality, cost, schedule and user disposal.

From [24], the Institute for Defense Analysis (IDA) Report R-338 defines concurrent engineering as ‘a systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. This approach is intended to cause developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule and user requirements.'

The term concurrent engineering has been used to describe cross functional teamwork in new product development. Concurrent engineering is sometimes used synonymously with the term *simultaneous engineering,* which means the simultaneous performance of all the engineering functions in a manufacturing company throughout the new product life cycle. Concurrent engineering and/or simultaneous engineering provides the product design, the quality engineering, and the manufacturing process engineering all at the same time [24].

According to NASA RP 1358 [19], concurrent engineering is more of an approach to quality management than a technique, and is an interaction of disciplines during the design but before production. Concurrent engineering also shortens and makes more efficient the design-to-development life cycle by employing the interactions of functional disciplines by a cross functional team, and reduces costs during that cycle.

It is an interaction between technical disciplines during the design phase to produce a more robust design prior to production. It is more of an engineering approach to quality management than a technique. This approach attempts to link and integrate, from the start, all elements of the product life cycle from conception through to disposal.

Concurrent engineering focuses on both the product and the process simultaneously. One way of doing this is through multi-functional teams consisting of engineers from several departments. In this way, each department will follow the complete process simultaneously rather than one department examining the design and then passing it on to the subsequent department(s).

The degree of success in utilising concurrent engineering is dependent on the degree of cooperation between the multi-functional team members. In addition, a significant amount of time and money are required at the start of a program to perform the coordinated planning. It is often difficult to to do this, even though there is an overall money and time saving. Finally, if the design is pursued by projectised teams then it can be difficult to capture the knowledge within the organisation or to employ it within design decisions.

The following characteristics may also be considered during the process:

- Development;
- Maintainability;
- Reliability;

- Safety;
- Verification;
- Logistics;
- Manufacturing;
- Training;
- Deployment;
- Operations;
- Support;
- Disposal.

Many techniques may be used to in the application of concurrent engineering. These include quality function deployment (see section 2.2.6), brainstorming, statistical process control (see section 2.2.7) etc.

According to Evans [29], concurrent engineering can be defined as 'the delivery of cheaper, better, faster products to market, by lean ways of working, using multi-disciplined teams, right first time methods and parallel processing activities to consider continuously all constraints.'

This means that all non-value adding processes will be removed from the design cycle, and resources will not be used to decrease the design cycle. Right first time methods include QFD, design for assembly, and design information will be stored and manipulated through the use of tools such as CAD etc. Concurrent engineering provides a framework for the efficient usage of computer tools and these may be used as a catalyst for changing to full concurrent engineering.

Studies considering the cost of a product have shown that 60 to 95 % of costs are determined during the design phase. Therefore, it is during this phase that savings can best be made. Moreover, the earlier the improvements are made, the greater the savings. The decisions taken during the concurrent engineering process are taken to ensure that the life cycle cost is reduced to a minimum.

Organisational Issues

According to Morris [30], concurrent engineering is not widely employed within the Aerospace industry due to conservatism. Morris argues that concurrent engineering is essential to improve customer focus, to fully utilise personnel and to the computing power available. To sustain the changes due to concurrent engineering requires strong leadership. He states that concurrent engineering can be summed up as teamwork, i.e. understanding all elements of the customer need and providing a balanced design of product to satisfy it, taking into account the complete product life-cycle.

An overall procedure for concurrent project management could be as follows [24]:

1. *Clarify the functional specifications:* This involves studying the customer needs, examining the market, clarify the company and marketing objectives, and finally confirming the functional specification;
2. *Write a detailed produce definition:* This again involves studying the competition, identifying and establishing the cross functional teams, and then selecting the design concept and detailing all aspects of the physical product;
3. *Describe the product:* This details the process of developing the product, including all of the required tasks;
4. *Generate a plan network:* List and prioritise all tasks and activities which constitute the project. Draw a plan to indicate the configuration of the activities, and finally study the resources;
5. *Validate the resource allocation:* Draw up a work breakdown structure and obtain approval from the resource managers for the required assets;
6. *Cost schedule:* Generate a cost schedule;
7. *Report:* Report on the plan to the company management.

Wiskerchen [31] states that Dynamic Systems Engineering (DSE) provides a framework for implementing concurrent engineering and TQM. He states that DSE is a way of identifying, quantitatively assessing and managing system performance and risk. The techniques described provide an effective way of reducing system risk due to a dynamic design and development environment, and these techniques can be implemented as standard features of concurrent engineering and TQM.

Campbell [32] states that configuration management, change control and risk management are very important to the process. The main issue with these is a clear accountability within the programme organisation and at the same time to ensure that all those who can contribute to or influence the process understand their roles. The latest proposed draft of MIL-STD-499B contains a requirement for the system engineer to maintain a "data base" of design decisions made during the process of going from the customer requirements to final design. There is a difference between presenting a design and presenting a reviewable design, where the considerations and decisions which led to the design are presented.

Petiau [33] states that the existing tools allow for many sophisticated analyses to be carried out, allowing an even greater number of solutions to be evaluated, and they allow structural optimisation to be carried out which assists with the structural design and its interactions with other disciplines. However, to fully take advantage of the concurrent engineering advantages, these tools will have to expand to become multidisciplinary. In addition, it must be possible to replay design iterations and their corresponding analyses to enable the knowledge learnt during the design process to be captured.

Campbell [32] states that the organisational model chosen within Shorts to achieve the high degree of required cross functional integration was Design Build Teams. These are co-located multi-functional teams of 10 to 20 people supported by engineering and other disciplines, and lead by a DBT leader.

According to Alford [10], the demise of systems engineering was due to recognition that systems were not satisfying all of their requirements. This lead to concurrent engineering, which in turn led to the new Integrated Product Development Team being integrated into the design process.

It is also noted that paper documents are too slow to support concurrent engineering [10]. Any solution to this problem will require some sort of electronic communication between participants. Some customers are already requesting an on-line view of decisions as they are made, rather than relying on infrequent meetings and presentations.

Enterprise Management

Enterprise management represents a template of how companies must organise, operate and perform to remain competitive and viable in the 1990's and beyond. Although businesses in the complex and engineered systems product sector have optimised their processes for many years, numerous dramatic changes are threatening their survivability [21]. Conditions such as reduced government spending, increasing domestic and foreign competition, cost of capitol and workforce skills are forcing a fundamental reconsideration of operational beliefs, processes, cultures, strategies and technologies. Five basic business conditions drive the mechanics of enterprise management evolution:

1. Interaction between the customer, prime contractor, subcontractor and vendor. Serial interaction is not longer viable due to product complexity, and therefore to assess risk and deliver the products within the tight constraints imposed requires a team effort;

2. Degree of program and product risk in cost, schedule and quality. With the increasing interest in life-cycle costs and risk management, these must be made part of the overall program;

3. Cross-disciplinary or functional interaction within systems. The fusion between design disciplines, functional business activities and inter and intra-organisational entities must be made manageable. These cross-functional teams require vastly different forms of communication, interconnectivity, measurable criteria and technical enablers;

4. Cultural and organisational adaption to "concurrence". Concurrent or simultaneous process activities remain difficult to achieve. While systems engineering allows tools which give synthesis of requirements, the task of eliminating individuals to eliminate old practices remains daunting. Getting the cultural barriers removed and organisational behaviour changed is crucial;

5. Evolving optimisation perspectives between user and enterprise based resources. These delays with system optimisation itself, and is primarily directed at automation technologies. As new product technologies have driven design tool technologies, their applicability to broader enterprise automation optimum has decreased. Design and engineering tools are becoming more specialised and therefore further removed from mainstream integration with enterprise systems.

2.3 Project Management Case Studies

Much has been written about project management, and especially concerning Systems Engineering due to the debate about MIL-STD-499. In the Aerospace field, there are many abstracts referring to research concerning space projects, but fewer directly relevant to civil aircraft. One of the major civil aerospace projects is the Boeing 777, and this is used as the prime example here. Others have been included to illustrate the use of modern methods or techniques.

2.3.1 Boeing 777

When the Boeing 777 concept studies began in 1987, one thing was clear; the requirement to produce an aircraft to meet or exceed all customer requirements (economics, mission capabilities and features) and that is preferred by the airlines [34]. Proven quality management techniques and philosophies such as mission statements, problem solving processes that are both identified and used, and clearly defined supplier-customer relationships across organisational and corporate boundaries, are integral to these efforts.

The Boeing 777 mission statement is: *"Working Together to Produce the Preferred New Airplane"*. Customer requirements are incorporated 'up-front', and there is one principal objective - to produce a high quality, service ready aircraft for May 1995 [34].

The core of the Working Together concept is the Design / Build Team (DBT). Representatives from manufacturing, quality assurance, reliability, material, customer services, weights and other affected disciplines are intimately involved in component and subsystem design processes from the very start, and are co-located with the designers on over 250 teams. Customer airlines provide service-based design input to several DBTs. At system level, over 20 Integration Teams are staffed by managers from technical and support disciplines, with many assisted by customer engineering managers [34].

The principal DBT software tool is Computer Aided Three Dimensional Interactive Application (CATIA). The engineering data for the Boeing 777 is defined under this system, using three-dimensional models of the parts and assemblies. Digital pre-assembly allows the designer to highlight interfering parts, even in other systems; permits manufacturing engineers to assess parts for producibility; and lets both make corrections before the designs are released for production. There are also benefits for product support, maintenance activities such as check out, access, removal and also installation. Support equipment can also be produced concurrently, and maintenance manuals produced using the same CATIA data [34].

Concurrent product/process definition is expected to give savings in several key areas [34]:

- Savings in design/development time, material and manufacturing;
- High cost reductions due to the cost of change, error and rework;
- Reduced fit and interference verification on first article parts and tooling;
- A lessened need for full scale mock-ups;
- Higher quality customer support.

The customers defined the aircraft, whereas Boeing designed the aircraft [34]. What evolved from the Airline-driven input was the “Market Driven Airplane” – basic design features on which there is customer consensus, configuration options which can be incorporated with less impact, and thus fewer unique changes. Boeing also introduced flexibility into the design, such as a high degree of interior flexibility [34]. This is addressed on the same level as economic and mission capabilities. The expected results are a low-cost high-quality service-ready aircraft to be delivered on time. The design requirements were market-driven, and the customer was integral to the whole process.

Organisational Arrangement

Boeing used a modified matrix management structure with a number of chief engineers who are responsible for end item functionality, reliability, maintainability, producibility, cost and certification [11]. There is a transitional division of responsibility into major functional areas, such as propulsion, structures, avionics etc. Below each Chief Engineer, are those aircraft systems corresponding to the appropriate major functional area. In addition to these Chief Engineers, a number of Chief Project Engineers have been assigned to be responsible for integration across the aircraft.

Chief Project Engineers are responsible for the integration of [34]:

- Aircraft requirements;
- Aircraft configuration design;
- Aircraft systems design;
- Performance, certification and test;
- Production plan compliance;
- Flight deck and crew operations;
- Customer service activities.

The use of systems engineering on the Boeing 777 began in Autumn 1989 with the creation of the Chief Project Engineers responsible for systems integration [34]. These activities may be divided into three types:

1. Airplane systems development - the process of developing an aircraft system in an efficient manner;
2. Systems integration - the process of ensuring the coordination of parallel system development;
3. Production integration and support - the process of ensuring proper installation of systems into a structure so that the final product is integrated and supportable in the future.

For each of the 65 individual aircraft systems, a number of documents were produced [34]. These include:

- A system development plan - summarising tasks, deliverables, schedules, resources etc.;
- System requirements and objectives - defining system requirements and objectives flowing down from the airplane level design requirements, including those requirements with interfacing systems;
- System analysis including functional hazard, failure and reliability;
- A system description;
- A system specification, where applicable.

Concurrent product design and development was ensured through over 270 Design Build Teams (DBTs) [34]. These teams are supported by members from production, engineering, suppliers, customer service and training, and in some cases, representatives from the airlines. These teams are defined around individual aircraft systems.

Team leaders have a dual reporting line, to their related functional managers and to the 777 Chief Project Engineer. Each team also has an engineering leader and a manufacturing partner for the design stage. When the development stage is over, the manufacturing partner will become the leader and the engineering leader will become the partner [35].

The Boeing 777 design features 100 % digital data release, where the design can be finalised without the need to build a model. This therefore reduces the need for physical mockups. The mockups are replaced by Digital Process Assembly, where system to system, and system to structure integration take place.

Systems integration is driving systems design into earlier phases. In turn, subcontracting comes earlier. And that, along with design/build, has lead to pre-selection of vendors who sit on selection teams to help develop specifications. This helps Boeing to generate a set of design requirements which the vendor 'has bought into'.

Method Verification

Boeing verified the accuracy of its techniques by building a nose section to check that the CATIA designed and pre-assembled parts fitted [36]. The aim of this was to show that a new set of design tools could be used to design and build an engineering component, together with the associated wires and fittings. The nose section is the most densely packed area of the aircraft. In addition, it was also used by some design/build teams to evaluate the engineering human factors, and by the airline advisory panel to prove that the design was suitable for easy maintenance.

In addition, Boeing are using the CADDS 5 software to automate the process of developing wiring diagrams and wiring schematics for the complete range of civil Boeing aircraft. The wiring diagrams will be developed from CATIA-developed designs [37].

2.3.2 Short Brothers plc. / Learjet 45

Short Brothers plc., a company known for design innovation and world-class product development, has undergone a significant change in the way they approach the process of product development of large, complex products. Shorts has identified and put into practice a total-process-oriented approach to substantially raise the development productivity associated with complex projects [38].

The fuselage of the Learjet 45 was one of the most sophisticated in existence, and yet it had been developed in 40 percent less time than its predecessors [38]. Further, it demonstrated a tenfold improvement in part quality and part-to-part assembly quality. Other statistics suggested how Shorts had been able to achieve its design and manufacturing success. Overall part count had been reduced by 60 percent, while first-article rework had been reduced by 90 percent over their previous experience. Of greatest importance was the client, Learjet, who were extremely pleased with the fit, finish and end-to-end quality of the fuselage. For its part, Shorts was also pleased, but was already hard at work identifying where new improvements could be made in the design automation process for the company's next major project.

Shorts had little experience of concurrent engineering until they worked on the new Learjet 45 [32]. A concurrent engineering philosophy embracing design/build teams and the application of the latest CAD and CAM technologies was adopted to drive a strategy which included people, process and technology. This was implemented through investment in new facilities.

Shorts implemented concurrent engineering on this major project, instead of developing it on a smaller pilot project. An overall strategy was developed for the Learjet 45, which included:

- Design by multi-functional design build teams;
- The DBTs should be collocated;
- The design was to be solid modelled in CAD;
- The CAD models were to be digitally pre-assembled.

The DBTs are collocated multi-functional teams of ideally 10 to 20 people supported by engineering and other disciplines and lead by a DBT leader. Significant benefits were anticipated from application of the latest CAD/CAM technology, particularly in solid modelling and digital pre-assembly to provide a single shared database of product information for all of the teams.

The DBT team leader's role was quickly found to be demanding and time consuming, and therefore a specific course was developed to assist them. DBT leadership is now defined as a distinct role within the company, and corresponds to the manufacturing cell team managers who work in manufacture within Shorts.

Shorts found the use of advanced networking combined with sophisticated 3-D modelling invaluable in the development process. When material, manufacturing and programme information is combined with this geometry data, the payoff is even greater with respect to the CAD / CAM systems.

Design and Modelling Techniques Used

As with many other companies, Shorts' early experience with design automation technologies involved wire-frame modelling of component parts [38]. Shorts, with experience in aircraft design that goes back more than 86 years, had progressed to wire-frame modelling in the 1970-1980s.

Previous regional aircraft fuselages built by Shorts would typically require up to 9,500 structural parts. Based on historical data, these projects required a first-article parts rework ratio equal to 150 percent of person-days, and could require over 445,000 person-days to complete over a four-year period.

At the time they undertook the Learjet 45 project, Shorts had invested substantial research resources investigating alternative methods to improve design and manufacture. The company had developed experience with new technology including parametric and explicit solid modelling.

Solid modelling could offer a potential improvement of better than 30 percent in time saved, from 445,000 to 312,000 person-days. Many manufacturers use solid modelling today, and have experienced similar improvements over wire-frame techniques. However, as these companies know, the benefits of parts-based solid modelling does not extend to part-to-part assembly quality and the resulting rework from assembly interferences. Because of this, a parts rework ratio of 150 percent would remain constant and consistent with previous experience. Shorts were determined to identify a better solution.

Shorts knew that to achieve greater-than-incremental improvements, the company would have to implement farther reaching technology changes. To do this, Shorts ultimately adopted hybrid modelling, a technique that permits integration of multiple model technologies. This provides the opportunity for engineers to combine sub-assemblies containing numerous parts into fewer numbers of more complex parts, through using Hybrid Modelling techniques.

The pressure bulkhead of the Learjet 45 fuselage serves as an example of lowered part count. In previous fuselages, this bulkhead was an assembly of 68 moderately complex parts; however, on the Learjet 45, this was replaced by a complex 5-axis machined part plus simple, less critical parts, e.g., brackets, supports, etc.

In addition, reducing an assembly to a single part also simplifies manufacturing, production, assembly, and maintenance because there is only one part to manage through the production processes and its ongoing life-cycle. This significantly reduces the risk of delay to the program caused by part shortages and eliminates all potential problems with multi-part fit through poor quality. In addition, because these new complex parts are designed within the multi-discipline Design-Build-Team and Digital Pre-Assembly environment, their manufacturability and ease of assembly have already been considered.

Overall, Shorts found that by implementing hybrid modelling, the company could, and did, cut parts count from approximately 9,500 to 3,700, a 60-percent reduction. As a result, total design/manufacturing time would be cut to 125,000 person-days. However, first-article parts rework would remain at 150 percent if the traditional approach was used due to the inherent limitations of the serial discrete parts based design approach.

For the development of the Learjet 45, Shorts ultimately embarked on a concurrent digital pre-assembly strategy in an attempt to significantly decrease the typical parts rework ratio. This strategy would combine Computervision's CADDS 5 hybrid modelling technology with the company's CAMU (Concurrent Assembly Mock-Up) digital pre-assembly and EDM (Enterprise Data Management) software.

The CAMU environment gave Shorts' multi-discipline design build teams (structural, piping, wiring, stress, tooling, manufacture, inspection, assembly and support) capabilities to work concurrently, identifying and resolving multi-system problems as design development evolved. As a result, first-article rework was reduced to only 20 percent of the original person-days, rather than the 150 percent of person-days that had been typical. And, in fact, the first-article production fuselage was the best aerostructure ever produced at Shorts.

Concurrent digital pre-assembly is particularly effective in reducing design time while improving parts quality because it gives engineers a powerful tool for resolving design conflicts – and thus automating change – earlier than ever before in the overall product development cycle. Typically, concurrent designers are in conflict because they are competing to use the same limited space. Digital pre assembly minimises the cost of these conflicts as measured in time and dollars by creating an electronic definition which allows team members to see each other's work, thus making conflicts obvious.

Shorts has demonstrated that a digital pre-assembly strategy can and did drastically reduce the typical rework ratio. As a result, total design/manufacturing time would be cut to 60,000 person days.

For the Learjet 45 fuselage Shorts also used the project management and control capabilities of Computervision's EDM as a means of tracking all data and documentation as well as coordinating the activities of the team members. EDM promises to play an even greater role at Shorts in the future, as the company continues its transformation toward full workflow automation.

Lessons Learnt

In reviewing the Learjet 45 project, it was clear to Shorts that too much time was spent on processing part information [38]. Part-processing person-hours were equivalent to part modelling person-hours. This happened because the status of information relating to parts and product configuration was not visible in the process.

For the new Global Express program, Computervision (the suppliers of CADDS 5) are working with Shorts to develop a new EDM workflow strategy to improve information flow and visibility and to establish much tighter integration of the key design and manufacturing systems using a framework. The EDM workflow system will provide a much improved product structure modelling and information attribute capability using EDMVault, CAMU and Configuration Access, a process workflow capability based on EDM Projects to ensure users have better visibility of the status of the evolving product definition and a change control capability to completely automate the processing and notification of change. Integration of EDM with project planning and process planning systems will ensure that all product information is instantly available to relevant users.

These new capabilities will help eliminate wasted time, and the associated costs of wasted time, from overall product development processes. In terms of this analysis, the EDM workflow capability is projected to reduce the process time required to check and release parts by at least two engineer-days for every simple part, and up to five engineer-days for complex parts. Overall, it will have the effect of taking a further 10,000 engineer-days out of the product development process of a fuselage.

The Shorts' analysis shows why world-class manufacturing organisations are increasingly focusing their strategies on modern design methods. To quote reference [38], 'the importance of part count reduction and to what extent the feasibility of designing complex parts in lieu of part assemblies can have on reducing cost and cycle time; The crucial role of digital pre-assembly in the complete product development cycle and the impact of "right first time" on the current level of design change from manufacture, assembly and support, including a view of the extent of wasted engineering time, the cost of scrap and the extent of delay because of poor quality information; The extent of information gathering and thinking time in the total part design cycle and an understanding of how EDM can provide better visibility of, and access to, this information, i.e., online standards, best practices, etc.'

2.3.3 Airbus

Although little has been formally published concerning systems engineering at Airbus, much may be derived from what has been written externally. Airbus are moving towards a CADDS 5 CAD system, which is similar in nature to the CATIA system used by Boeing for the 777. This provides similar functionality in terms of configuration control, interference and geometry control across multiple teams through the use of a central database. Interfaces are clearly defined, and the teams then have to design their components to meet the interface boundaries. This is being introduced from the A330 onwards.

All of the Airbus partners are moving towards a concurrent engineering-based product development process [39]. Of particular importance is the ability to manage the information, activity and interaction of design teams concurrently, and therefore all of the partners will be able to work together using CADDS 5.

Airbus has chosen Computervision as its partner in moving to a fully integrated, collaborative product development methodology known as Electronic Product Definition [40]. With EPD, Airbus wants to be able to coordinate design, assembly modelling, manufacturing, maintenance, and other product development activities across the consortiums primary vendors, its partners and suppliers. Eventually, Airbus hopes to streamline operations to the point where a single bill of materials can be used by all Airbus partners and suppliers for each new aircraft.

To get an idea of the potential for EPD at Airbus, one needs to look no further than the initial 'proof of concept' pilot that Airbus undertook in 1995. The pilot covered all aspects of Electronic Product Definition, from modelling and assembly to multimedia-assisted shop-floor instruction, and it offered proof of concept for these objectives:

- Time-to-market for new aircraft design can be compressed substantially by overlapping functions that have traditionally been performed serially;
- Business-process redefinition could facilitate 'design-for-manufacture' and improve right-first-time results;

- A single product structure could be shared by cross-functional design teams, working concurrently at various locations, without conflict;

- Computervision's EPD could help Airbus Industrie produce 'derivative' aircraft to quickly capitalise on newer product niches, an important competitive advantage.

Airbus Pilot Project Details

British Aerospace Airbus wanted to see a full range of off-the-shelf software, including CADDS 5 hybrid modelling, wire harness design, various analytical packages, numerical control (NC) computer-aided manufacturing (CAM) software, CAMU (Concurrent Assembly Mock-Up) digital pre-assembly, and Optegra life-cycle data management software. Also, British Aerospace Airbus and Computervision constructed the pilot to evaluate the concurrent engineering benefits of EPD both for derivative designs and for new projects.

For the derivative design, CADDS 5 software was used to model major components, such as the inner rear spar and ribs, of a large aircraft wing. For the ground-up project, the software helped a 25-member design-build team create an Electronic Product Definition of a small aircraft wing. To model a multi-site design process, the evaluation took place across British Aerospace Airbus sites in Filton, Bristol, where 12 workstations were placed, and Chester, located about 180 miles away, where team members had three workstations.

Firstly, the design team was assembled. It consisted of 25 full-time members, drawn from engineering, manufacturing, purchasing, and aerostructures, with support from an additional 25 professionals drawn from those functions as well as from marketing and finance. Rather than commencing with detail design, the team began by defining an overall product structure that would be best suited to ease of manufacture. They defined major wing components and their design relationship, and also entered key characteristics, such as target time frame, weight and cost, and potential suppliers, that would later be critical to manufacturing. Additionally, the wing was divided into three design 'zones', leading edge, trailing edge, and wingbox, to facilitate and focus overall team-design responsibilities.

With the product structure defined, team members moved to conceptual studies and wing-surface configuration design, creating CAD geometry in areas of critical interfaces, such as where ribs, engines, and pylons attach to the wing and where the wing joins the aircraft body. At this point, certain information can be shared with key suppliers and customers, letting them begin their involvement a mere tenth of the way into the design process. Normally, these partners would not be involved until the design process was at least 50 percent complete.

Detail Design, Manufacture, and Assembly

The next stage in the pilot was wing pre-design, where initial rough models were refined via the addition of more precise definitions. At this time, the team was able to begin striving for optimisation of weight, strength, cost, and manufacture.

Following that came detail design, where detail component design takes place within the context of the overall product structure. This ensures that specific design details do not conflict with the larger product assembly objectives originally set forth by the design team. Even while detail design was underway, engineers were able to begin tooling manufacture. In wing design, a critical aspect of manufacturing engineering involves assembly of the giant manufacturing jigs that are used to position wings during final manufacture.

Because critical manufacturing-related information such as assembly sequences, parts interference, weights, and centres of gravity is already built into the product definition, tooling suppliers can get started on the jigs and related tooling even before final assembly designs are released. This contributes substantially to compressing time to market for new aircraft.

Product Demonstrations

Throughout the Airbus pilot, specific CADDS 5 software tools were tested as part of the major process phases. Life-cycle data management software was used as the primary EPD infrastructure. This employs a unique navigation facility that groups product-structure components into a tree-like hierarchy. By clicking on any component, team members can view all related components and can select any relevant information, from target vs. actual weight to cost and revision number about that component.

Also, the it was possible for engineers at both UK test sites to access design information stored in the Filton-based design database. Another tool makes it possible for the engineer to call up a three-dimensional, rotating graphic depiction of the component, highlighted within its larger assembly. Interference checking and other such tests via a digital prototype was also used throughout the evaluation period, rather than having to build expensive (and static) physical prototypes. It was tested both for wing design and for designing manufacturing jigs, and demonstrated a large timesaving potential.

The Use of CADDS 5 within Airbus

In addition to other major projects, Airbus is now in the process of putting EPD to work on a new aircraft design, the A3XX. Scheduled to go into service as early as 2002, the aircraft will be in the 500-650-seat range, and will compete with the expected large-capacity 747 derivatives.

In preparation for the A3XX development, the three Airbus partners are training users, and undertaking a variety of pilot programs as described previously. For instance, Aerospatiale has used EPD software for fuselage cross-sectional modelling; Daimler-Benz has performed assembly modelling to test the feasibility of installing circular stairways and under floor bedding in some first-class sections and British Aerospace Airbus has embarked on several large-scale projects involving modifications to existing airframes, such as the A330. Also, the three Airbus partners have formalised a program for identifying and cultivating synergies in their product development processes. They have formed a process-improvement group called ACE, for Airbus Concurrent Engineering. Members of the ACE team are charged with evaluating design-process similarities and contrasts among the Airbus partners and then recommending changes that will maximise their efforts and minimise process conflicts.

Furthermore, the ACE team is working closely to determine what next-generation EPD software tools will be needed. This kind of early involvement in EPD product design benefits both Airbus and Computervision. For Airbus, it results in newer software tools that closely match its needs; for Computervision, it injects highly focused customer input into the Research and Development process.

The goal to produce a single bill of materials that can be used across the Airbus partners will soon be closed due to powerful configuration management features. These features will let the Airbus partners, and, eventually, their suppliers and other partners, work from the same product configuration data, no matter where they are located.

2.3.4 HR Textron

HR Textron Inc. is a world-renowned supplier of sophisticated aerospace flight control systems [41]. Through continually improving its product development methods, HR Textron has dramatically shortened its lead times; in some cases by as much as 30 percent. CADDS 5 has enabled HR Textron to reduce its product cycle times. For example, the normal lead time of a flight weight/production configuration of a Cessna flight actuator has been reduced by approximately 30 percent, and the time taken reduced from approximately 12 to 18 months to six to twelve months due to rapid prototyping. It is now not uncommon for there to be flight configuration hardware before the actual drawings have been produced.

In addition, the machine tool path used to produce the hardware is verified with the CADDS 5 program, thus saving much actual proofing time. In one example, HR Textron was able to machine a hydraulic manifold in one week rather than the typical three to four months it can often take.

CADDS 5 has also improved HR Textron's ability to demonstrate new product designs to customers and subcontractors. The object can dynamically be manipulated to show all views of a part due to the highly graphical nature of the modelling package and also allows realistic images to be produced of how a finished product will appear. This capability also makes it easier for customers to have input during the product development process.

A database program is also used to keep its projects on track. The database has information on the parts, parts assemblies, and the various attributes of each. It also tracks design revisions and helps to control and manage engineering change, which is essential in large projects. This information is located in a central repository.

2.3.5 Lockheed Martin Darkstar

DarkStar, the next-generation reconnaissance aircraft complementing such famous Skunk Works aircraft as the U-2 and SR-71 Blackbird, is intended to provide high-altitude, all-weather, wide-area surveillance.

DarkStar is designed for fully-automated take-off, flight and recovery and will operate at altitudes in excess of 45,000 feet for eight-hour periods or longer. Its 8,600-pound gross weight is packed into a sleek, low-profile design: its height is just five feet and length a mere 15 feet, but its wing span stretches 69 feet. The aircraft's sensitive radar and electro-optic sensors are designed to provide the military with bomb damage assessment and detection of enemy missile systems in near real-time.

IBM / Dassault CATIA CAD/CAM software enabled aircraft manufacturer Lockheed Martin Skunk Works to design and build DarkStar, the world's most advanced unpiloted reconnaissance aircraft, in a fraction of the time and resources normally required for a project of this magnitude. Using CATIA enabled Lockheed Martin Skunk Works and DarkStar partner to meet a very aggressive schedule, in part, by eliminating the need for expensive mockups.

The first DarkStar unpiloted vehicle was rolled out nine months after a team of 50 Lockheed and Boeing designers started the project. Similar projects have taken several years and have required hundreds of designers to complete. CATIA delivered the solutions to support the integrated approach to building DarkStar,through networks of colleagues and suppliers working off the same aircraft model in a virtual enterprise. For example, wing designers at Boeing in Seattle and fuselage designers at the Skunk Works in Palmdale, California, could simultaneously access and collaborate on specific designs. The result was a perfect fit at the first assembly.

Lockheed Martin selected the IBM RS 6000 for its outstanding performance running the CATIA design package and its overall price/performance. Precision throughout the building process was especially critical because DarkStar is a composite aircraft, built from composite materials instead of metal. Tooling began from the CAD models that were created on the system in just two weeks.

Darkstar is the first military aircraft to have been designed without the creation of physical mockups, which helped to reduce costs and speed the design process. Expensive wind tunnel testing was eliminated, for example, because designers were able to analyse the 3-D computerised CATIA for various environmental stress factors. Radar cross-section analysis on the CATIA model also gave designers assurances that the plane would have an appropriately low radar profile.

The IBM system used to run the CATIA software was also used to run Nastran, a structural analysis package that allows engineers to simulate stress on the aircraft's fuselage and wings without building expensive prototypes. The system's server also supported a network of PCs on the factory floor, running resource planning and quality assurance applications. This allowed engineering and manufacturing to collaborate more closely and efficiently than ever. CAD models were sent directly to the factory floor, giving manufacturing real-time access to data required to perform the manufacturing process.

2.3.6 Gulfstream V

The Gulfstream V is a large advanced business jet aircraft, capable of linking New York to Tokyo nonstop at high speeds and in great comfort. Its designers have used CATIA for three years in the design and development of the Gulfstream V [42]. The fuselage was built in 34 days less than planned to an exceptional quality level. Using an electronic mockup enabled them to assemble the aircraft more efficiently.

The electronic 3-D mockup which enabled them to move forward concurrently in designing, developing, checking and integrating all its parts, eliminating the traditional separation between the design and manufacturing. The complete aircraft, including cockpit design and cabin furnishings, was modelled within CATIA.

2.3.7 Saab 2000

The Saab 2000 is the new generation of regional aircraft with jet-like performance and better cabin comfort than previous generations of turboprop regional aircraft. It was initially equipped with mechanical flight controls, excepting the hydraulically actuated rudder [43]. It was discovered that a simple longitudinal fly-by-wire pitch augmentation system was required due to some minor longitudinal stability and control problems. The fly-by-wire elevator system also reduces maintenance time, weight and simplifies the design, and it is based on the rudder actuation system.

Saab initially specified the fly-by-wire elevator system should be designed, tested, certified and delivered within 18 months. In addition, it was to be affordable and capable of being retro-fitted. Saab formed a Design/Build Team to develop, qualify and install the system. Within the DBT, further subgroups were formed.

The augmentation system was designed to provide artificial stick forces, variable stick to elevator gearing, a serial trim function dependent on airspeed and stability augmentation based on normal acceleration, airspeed and flap position. This gave increased stick forces and a reduced aircraft response with flap deployment. Finally, the overall system reliability was designed to meet or exceed the following failure probabilities:

1. P(loss of function) of 10^{-9} per flight hour;
2. P(elevator hardover) of 10^{-9} per flight hour;
3. P(flutter risk) of 10^{-9} per flight hour;
4. P(loss of stability augmentation) of less than 10^{-5} per flight hour.

Flight control power duration is dependent on gliding time from max altitude. A fixed base simulator and an iron bird was used for failure analysis and reliability testing. A second prototype aircraft was included in the testing process as soon as the flight control system configuration was frozen. The simulator was used for certification of failure cases after having been validated against the actual aircraft data.

Finally, DBTs were used within a defined task for limited periods and were disassembled when the task was complete. It was found that certain portions of the flight test program were more critical than others, with with the aerodynamic data verification proving to be the highest priority. This process ensured that any changes required during the testing phase could be left to an improvement phase. This is a system optimised for its operators, and not just for safety.

2.3.8 Summary Comments

From the above descriptions of the actual case studies, the following key points may be derived:

- Some form of electronic data management is required to control the information flows;
- All of the programs used concurrent engineering methods to reduce costs and risk, and to minimise change;
- A central data repository is required to facilitate the design process and to ensure that the most up to date design is always available;
- Design and Build Teams are used to good effect, effectively focusing on one particular component of the product. In addition to this, steps were taken to ensure that co-located teams were used;
- The use of Computer Aided Design tools enables additional analysis to be performed due to the central design repository, such as radar cross section analysis and access to parts for maintenance by electronic mockup;
- The projects all had a strong customer focus to ensure the final product was what the customer wanted;
- There was a reduced need for physical mockups due to the increased use of computer generated models;
- The production needs were considered early on so that the number of production problems experienced was small as possible;
- The customer focus together with the design process used was used to help to minimise life cycle costs;
- The process was documented so that decisions and responsibilities were traceable, but the amount of documentation was kept to a minimum;
- The use of tools such as CATIA helped to produce a more efficient design in terms of reduced part count;
- The amount of reworking required was kept to a minimum through getting it right first time;
- Consistency was improved through analysis of the design process, and by using a rigorous design process.

2.4 Generic Regional Aircraft Project Description

The project under consideration here is the design, manufacture and test of a Generic Regional Aircraft. This is used as an example for the project management techniques described within this report. The use of an example enables the techniques previously described to be used with a specific project in mind, and their advantages and disadvantages to be discussed.

Since this thesis work is being sponsored by British Aerospace, use has been made of their engineers in defining realistic timescales for the design and development process. However, it must be emphasised that the process under consideration here is generic and therefore does not refer to one particular aircraft or series of aircraft.

Again, due to the nature of the programme, the project management analysis will focus on the Avionic systems, such as the fly-by-wire system, the flight management system and the supporting systems (such as electrical and hydraulic). The rest of the aircraft design process will be modelled at a superficial level, while these systems will be modelled in much greater detail.

The following objectives are sought:

1. To determine if there is a 'critical path' in the aircraft design and development process using the data contained within the process model;
2. To determine which decisions made at the start of the project influence the principal components of the project;
3. To illustrate how the project management tools described may be used to reduce the design time, or to enable a better design to be produced.

2.4.1 Assumptions

The following series of facts have been assumed about the aircraft design:

1. The aircraft will be a Generic Regional Aircraft, with approximately 100 passenger seats;
2. Although modern technologies, such as fly by wire, will be used, no technology will be proposed which has not been used in normal airline service before;
3. The airframe will be manufactured by the Aircraft manufacturer in question;

4. The avionic systems will be sub-contracted out, and allowances must be made for this during the project tendering;

5. The aircraft must be certificated in line with standard certification practices;

6. The aircraft will have a 'conventional' flight management system / flight control system. Tools such as QFD imply that decisions such as the functional separation into separate systems be made at a late stage. The assumption has been made here that the most favourable functional division is like a 'classical' modern fly-by-wire aircraft.

2.4.2 Project Phases

This section is intended as an outline only, as the detailed process would have to be agreed with experts from each of the functions. However, it should act as an aid to the basic process, and the information flow which is needed. The final document would have to be produced with the actual suppliers/teams since they know their capabilities better than we do. Much of the information contained within has been generated from conversations with people representing the different functional areas involved.

The systems engineering process comprises 5 phases, labelled A to E which are described below:

Phase A. Conceptual trade studies

This phase is intended to identify the basic concept and options. It is expected to last from the start of the project for the first 6 months. It represents the first part of the feasibility study on a conventional project, and it results in a number of different solutions to the problem, with 'black box' requirements, i.e. the requirements are considered on a functional level alone, with little, if any functional allocation to specific systems or specific contractors. It is performed in this way to ensure that the design meets with the overall customer requirements, and therefore customers need to be considered during this stage. During this phase, the following actions need to be performed.

- Work with the customers to define an initial target market / segment, cockpit, mission profile, reliability, maintainability, Direct Operating Cost requirements etc (customer needs);

- Define possible aircraft configurations;

- Select the best configuration for future work;

- Start investigating the different control law configurations on another aircraft;
- Produce a black box set of requirements;
- Decide on the project management structure for the program;
- Decide on the project management issues;
- Work with the DBT leaders to confirm timescales and resource requirements;
- Verify that an engine is/will be available - the engines for the Boeing 777 had a 5 year development time;
- Produce a sound business case for the aircraft;
- Identify potential launch customers;
- Identify the technology risk areas, and investigate solutions;
- Decide on the certification basis for the aircraft.

At the end of this period, the aircraft concept to be followed will be known (i.e 2 or 4 engines, baseline configuration etc.) However, no specific solutions to detailed problems will have been formulated. The performance requirements will be known, for example the required range, payload etc. In addition, reliability targets will also be known, such as dispatch requirements and other which could influence the detail system design.

It is envisaged that flight control law design work will have started. This may, or may not be with the aircraft under consideration. As long as a similar aircraft is used, control law design can commence to identify the basic control law philosophy to be implemented. However, the results of this study may not be available until the end of the next phase (phase B).

The results of this phase should enable the following decisions to be made. Since a preliminary aircraft sizing will have already been completed, the requirement for a specific type of flight control system should have already been considered, i.e. should electrical signalling alone be used to give weight savings, is some sort of augmentation required due to predicted minor differences, or should a full fly-by-wire system be proposed due to major projected problems. This information is required if the proposals for prospective flight control system vendors are to be realistic.

The requirement for a specific type of flight control system will also have implications on the hydraulic and electric systems, as well as the position and type of control surface. For example, the saving in cost by not having to design a FBW system may be offset by a weight penalty, and there may be flutter or control force requirements for a mechanical control system. This again would not be confirmed until the end of phase B, but it is the type of information which needs to be considered during phase A.

Phase B. Conceptual Definition

This phase is intended to take the basic concept and turn it into a more optimised design. It is expected to last from 6 to 18 months, which for a traditional project would be towards the middle of the pre-development phase. At the end of this phase, it is expected that the final aircraft configuration will have been frozen, and the basic aircraft dimensions, performance characteristics and weights will be known.

In addition, the black box requirements from Phase A are taken and expanded into a more detailed functional level. Suppliers are also invited to tender for specific components of the system, so that more detailed solutions may be found. The 'design independent' customer requirements must be considered all of the way through though since these should form the basis of the design. During this phase, the following actions need to be performed.

- Confirmation of the customer needs;
- Generation of a cockpit philosophy and mockup;
- Continuing the design of the airframe;
- Working towards the control law final concept;
- Production of the final functional specification from a black box set of requirements, including functional distribution amongst systems;
- Formation of the main DBTs, even with reduced manpower;
- Setting up the CATIA system;
- Forming working relationships with the subcontractors;
- Defining system interfaces (i.e. how should one aircraft system or structure interface with another);
- Finishing partnership discussions (if other major partners are involved) and having defined interfaces between their components;
- Working with the prospective launch customers;
- Producing an overall programme for the design phase.

At the end of this period, the configuration will have been frozen, therefore confirming specific information such as size, mass, engine requirements, performance etc. In addition, there should be a reasonably detailed aerodynamic model of the aircraft available, meaning that specific control law work may be started on this aircraft. This should coincide with the completion of the control law trials, which would hopefully have confirmed the suitability of specific control law concepts, and will enable the most likely solution to be proposed. In addition, further work would have been carried out with the prospective customers, enabling the launch customers to be confirmed, although the instruction to proceed will not have yet been signed.

At the end of this phase, the decision to proceed with FBW will be known, and the characteristics of that system will also be known, i.e. is electrical signalling only required or a full super-augmented fly-by-wire system? In addition, the major systems requirements will be known, such as the number of hydraulic systems, actuators, electrical requirements etc., including the system behaviour under failure conditions.

The aircraft cockpit design philosophy will also be known. For example, the basic display design should be known, since this is dependent on the control law characteristics (which are known) and cockpit inceptor types (which are also known).

Generally, the basis under which the aircraft is going to be certificated, the programme funding status and the required resource requirements should be known. The major deliverable during this phase will be the final pre-detail design specification.

Phase C. Design and Development

This phase is intended to take the detailed concept, and to transform it into an optimised design. It is expected to last from 18 to 42 months, which for a traditional project would be from the middle of the pre-development period to the middle of the development period.

During this phase, the following actions need to be performed.

- To work with prospective systems manufacturers to tender for appropriate systems;
- Selecting the appropriate subcontractors as required;
- Confirming the actual design, and finalise the configuration;
- Performing the detail design;
- Confirming the need for fly-by-wire or any other augmentation in the simulator;

- Choosing the most promising control law type;
- Producing prototype hardware and software.

At the end of this period, all wind tunnel testing will be complete, except for development modifications. This enables the final development control laws to be designed, and the flight simulator design can commence. In addition, much of the design work should be complete, with a final aerodynamic model being ready, and much of the flight control system and flight management system hardware and software should be completed.

Phase D. Fabrication, Integration, Test and Evaluation

This phase is basically the production phase for the aircraft, and should last from 42 to 60 months from project conception. The 'almost' completed final design may be finished, and production started. Some long term testing may also be required, such as high reliability items which require a large number of test cycles.

During this phase, the following actions need to be performed.

- Commence building the aircraft;
- Be ready to start using the Iron Bird for actual hardware certification;
- Use an in-flight simulator during this phase (as with the SAAB 2000) if required.
- 100 % document release should have been reached 6 months into this phase
- The production of long lead time items should have started.

At the end of this period, the aircraft will almost have completed static testing, the aircraft will almost have a flight release and the long lead time items, and most of the other items will be under production. The flight control system hardware should be finalised, and the production FMS should be nearing availability.

In addition, the static test specimens will be finished, a cockpit section for the training simulators will be available and production FCS hardware will be under test.

Phase E. Operation

This phase is basically the test phase for the aircraft, and should last from 60 to 78 months from project conception. The 'almost' complete aircraft may be finished, or in final assembly, and the production will have started.

The first flight is expected to be 6 months into this phase, and flight testing is expected to last a year, with certification of the aircraft occurring towards the end of this phase. It is envisaged that most of the problems should have been troubleshot before the actual testing phase, but minor modifications may be required during this phase to systems or the design of the aircraft itself. During this phase, the following actions need to be performed.

- Certification of the aircraft;
- Static testing is started;
- All test flying is performed;
- The iron bird rig will be in use;
- Final modifications to the actual flight software as a result of the flight tests may be made;
- Aerodynamic model validation shall be made from the flight test data;
- Commissioning of the training simulator will be done;
- Modifications required as a result of the certification and test process will be performed;
- The design processes shall be validated so any problems can be identified and resolved 'next time';
- The customers will be consulted to make sure they are happy with the product.

At the end of this period, all testing will be complete with a certificate of airworthiness having been issued. Route proving will have commenced, and the majority of it should be complete. Pilot and groundcrew training should also occur for the launch customer(s) so that they may commence operations as soon as possible. It is possible that this phase may go on at a lower level for up to 2 years after initial service entry due to reliability and in-service problems. The major deliverables will be a certified service-ready aircraft, which the customers are happy with, and which (ideally) fulfils the initial customer needs.

2.4.3 Aircraft Design Description

This section describes the proposed work to be carried out at each stage of the process, and the high level relationships between individual systems and components.

It has been assumed that a large amount of the systems work will be carried out by external contractors who have a greater amount of experience with the specific design of complex systems, compared to the airframe manufacturer. The involvement of these manufacturers is stated as appropriate.

The actual process model is described within appendix A. This contains a list of the tasks used to generate the process model, together with a description for each task and the dates between which this task should be performed.

This model was implemented within the Microsoft Project software [44]. The tasks are defined together with any timescales or time requirements and the nature of any links or relationships between individual tasks. The software then calculated the critical path, which is the sequence of tasks which define the earliest possible finishing date. Variations could be made to tasks to assess the effect of performing a task quicker, or modifying the relationships between tasks so that a task could commence before another had finished.

The result was a series of scenarios which showed how the project's finish date depended on the tasks which came before it, and also how the effect on the project of removing a critical task, i.e. showing the next critical task. The critical path for the process is shown on the Gantt Chart in appendix A.

Flight Control System

The flight control system consists of two main components - the hardware and the software. The hardware design, one released should be fixed, though the software design may need modifications as the aircraft commences its flight testing. The hardware generally comprises the following components:

- Actuators (excluding the hydraulic system components);
- Air Data and Internal Reference system;
- Flight Control Computers;
- Databuses and associated wiring harnesses.

Although the hardware description would be determined during the actual design process, where the functional distribution would also be confirmed, it is likely that several components will be standard 'off the shelf' items. Therefore a classic hydraulic / electric / flight control system distribution has been assumed. The actual items of hardware used, and their functionality would be defined during the initial design process.

Air Data and Internal Reference System (ADIRS)

This system has again been included on the assumption that the systems being used here are conventional in nature, and a conventional ADIRS is found to be required from the conceptual trade study and conceptual definition phases. The requirements for the ADIRS are dependent on the signals required by the systems dependent on it, and therefore the Flight Control System and Flight Management System, or maybe the 'Black Box' data recorders will dictate the requirements. The interfaces between the systems should also be covered, i.e. should a MIL-STD-1553, ARINC 429 or ARINC 629 type of databus be used ?

Flight Control Hardware

The conceptual design of the flight control hardware ideally needs to be carried out during the conceptual definition stage. In this case, it would involve confirming that the aircraft would have conventional hydraulic actuators, with electrical signalling from the flight control computers as appropriate. This would need to be developed by a team comprising representatives from the airframe manufacturer, together with the various subsystem suppliers as appropriate. The actual system characteristics would have to be finalised by the end of the conceptual definition stage so that the different suppliers could start work on detailed design, i.e. the interfaces between the different components and the functionality of each component would have to be defined. The final hardware design would have to be confirmed towards the end of the design process.

Flight Control Software

The flight control software would be developed concurrently with the hardware. However, the software is not likely to be as critical as the hardware definition initially since the software would be designed to work within each piece of hardware, and therefore its interface is identical to the hardware interface. However, the software interface is dependent on the functionality of the system. Therefore, for the final hardware interface to be confirmed, the required software functionally needs to be confirmed. In the case of the flight control computers, this is the required inputs to the control laws, such as the required air data and inertial signals, and also the required outputs, such as the control surfaces which need to be driven. Hence this must be known at the end of the conceptual definition stage.

Control Laws

Due to the software requirements, the required inputs and outputs to the control laws must be known at the end of the conceptual definition stage. This does not mean that the actual final control laws are required, just detail stating the required inputs and outputs that they require. A method of preventing most information availability problems would be to make too much information available, i.e every possible air data, internal reference or other signal available. However, this would probably be inefficient in terms of data transfer, and may result in over-specified equipment providing information which is never used. Therefore, it should be avoided.

Flight Management System / Autoflight System

For the purposes of this discussion the Flight Management System (FMS) has been extended to include the communications radios and the cockpit displays, as well as the actual navigation and flight management systems and autopilot functions.

The required functionality would have to be determined by the customers in the initial trade studies and conceptual definition stages. However, to keep costs down, it is likely that the FMS would be based around an existing design (ideally one fitted in the aircraft from the same manufacturer if this was deemed suitable, and commonality was of importance to the customers). The interface between the FMS and other systems would have to be defined before the end of the conceptual definition, since the interfaces with the other avionic and electrical systems would have to be confirmed.

The displays would also have to be designed in collaboration with the control laws, since they tie in very closely with the flying qualities. However, this could initially be carried out at the same time as the initial control law conceptual work, and the requirements defined in collaboration with the control law requirements.

The same proviso is stipulated for the autopilot. It may be possible or desirable to combine certain autopilot functions with some of the low level flight control system functions so that low level autopilot and flight control system functions may be combined. This would again have to be determined during the conceptual definition phase, during discussions between the different contractors involved, after the black box requirements have been defined.

Airframe

The airframe has been defined as the major structural components including the furnishings but excluding the engines and systems. The basic configuration should be decided during the initial conceptual trade studies phase. Therefore the number and location of the engines should be known, along with a realistic mass, and the cabin configuration should be defined as a result of an initial market study.

During the second stage, the airframe configuration should be confirmed, with an accurate projected weight, and a fixed configuration. The short and long lead items should be known so that the long lead items may be considered for design. In addition, any special requirements for the airframe in terms of materials or manufacturing facilities should be identified so that special provision may be taken into account if necessary. Identification of any special items requiring either special facilities or a long lead time needs to be made.

The majority of the detail design will take place during the third phase. This includes the detail design and manufacture

Simulation

Once the aircraft model is available, it takes about 3 months to code on a typical engineering simulator. After this has been completed, the aircraft may be flown, and initial development carried out. The airframe aerodynamic model is likely to be finalised after approximately two years of development.

Documentation

The documentation is of fundamental importance in a project such as this. The information contained within the different forms of documentation is available within the different project teams, and to a certain extent, it is stored within the central repository if a CAD system of this type is used. The different forms of documentation required are listed as follows:

- Customer Documentation. These are the aircraft flight manuals, maintenance manuals and any other documents the customer may require;
- Certification Documentation. This is the documentation submitted to the appropriate aviation authority to enable certification to take place;
- Design documentation. This documents describes the design process taken, the decisions made, including the reasoning behind them and also gives details of the final design produced. This documentation is required principally for quality purposes, and if it is generated systematically, the aircraft will be a high quality product.

2.4.4 External Involvement

This section details some of the issues concerning avionic design such as when the parties concerned need to get involved in the aircraft design project and to what level.

Avionic Systems Suppliers

The choice of Avionic system supplier needs to be made before the instruction to proceed, otherwise they will not have sufficient time to perform the development process. However, in order to produce a request for tender, the airframe manufacturer must have a conceptual idea of the aircraft systems and how they will link together. Unless the systems supplier is being asked to bid for the complete systems package, the interfaces between the different systems must be known.

The initial conceptual systems arrangement may be defined in the initial conceptual stages. The proposed design here would include a general arrangement of the avionic system concerned, and any proposed interfaces with the airframe in general and the other avionic systems proposed for the aircraft. Feasible solutions would need to be proposed initially for the tender. This would require discussions at a high level within the avionics company to determine possible system arrangements.

After the tender has been written, it may be distributed to the different avionics manufacturers intending to bid for it. The principal contacts will be made at this stage since much more work will be required to confirm the proposal. It is expected that the bids will be received and the contract awarded before the instruction to proceed.

Customer

Obviously the customer is the most important person involved with the process since if the design does not meet customer approval, the aircraft will not sell, and therefore be a commercial failure. Therefore the customer should be involved from the initial stages all the way through the design process. Initially, the customer's requirements should be examined in great depth, and the possible solutions considered. This may only involve a small number of people from a few target airlines. Subsequently, as the design process progresses, more detailed customer involvement should be considered, for example maintenance issues should be discussed with airline maintenance personnel, if they are available.

In addition to this, target customers should be considered, plus any potential customers who may otherwise be overlooked. For example, the prospective aircraft may be required to be used in the armed forces for general or special duties, so these duties must be considered in advance. Although it may be prohibitively expensive to design an aircraft which meets both civil and military requirements from the outset, it may be useful to consider where the possible problems may be with a military variant, and how the design may be modified to help alleviate them. A good example of this are civil aircraft being required to be used as military transporters or in-flight refuellers. Some of these aircraft have required extensive modification to enable them to be used in the appropriate role. Some initial consideration may help to reduce this a little, and thus ensure that a potentially large market is still accessible.

2.5 Description of Information Flows within the Project

As with all situations where two companies are required to work together, with one as a contractor to another, there are certain items of information which are required before the process of tendering, and subsequently designing and developing may commence. This also applies to situations where two different groups within a company are required to work together.

For the purposes of this project, the airframe manufacturer, who is assumed to have overall control of the project is referred to as the 'manufacturer'. Any companies manufacturing components for the manufacturer are referred to as 'subcontractors'. The 'component' is the item under question which is being contracted out for design and / or manufacture.

The following comments refer to the information flows between contractors and manufacturers. These comments have been made in light of experience derived from defining the process model for the aircraft design project defined in appendix A, plus comments from the industry personnel interviewed.

2.5.1 Information Flows Between Contractors and Manufacturer

The contractors require a certain amount of information to enable them to both tender for the project, and then to enable them to execute the design and development process for their own component within the project. The information listed below is required for the initial tender and subsequent design, development and manufacture of the components in question.

- A functional description of the component being tendered for;
- A description of the interfaces between this component and the rest of the item under design (whether those interfaces be to components being designed and manufactured by the manufacturer or another subcontractor);
- A timescales for the design, development and manufacture of the component(s) under question;
- An expected time for entry into service, and some idea of the initial production volumes required;
- Any requirement for prototype or pre-production components, for test or initial operational use;
- A risk assessment;
- Any other relevant information (whatever that may be).

However, it is noted above that some of the information listed above assumes that a certain amount is already known about the project, such as preliminary timescales and functional requirements. In addition, it is necessary to set the prospective subcontractors a realistic task, since it is not generally acceptable to request a tender, specifying that the work must be completed in an unfeasibly short amount of time.

This implies that some initial work must be done during the planning stages to ascertain how long all items which are intended to be sub-contracted require for design and develop. However, this causes another problem in that it assumes that a generic set of system requirements is present. For existing systems, this is probably not too much of a problem since it will generally be possible to assume that the system has been designed and implemented before, and therefore a set of specifications, plus information concerning how long it takes to implement and any other relevant information will be available. However, for new types of system, or systems which have not previously been used in a particular application, it is necessary to research these items of information beforehand so that the information is available at the planning stage.

During the research period for this project, it was found that companies who were likely to be acting as subcontractors were desperate to obtain as much information as possible concerning the project at an early stage. The reason for this is to enable development to start and for them to obtain a design as early as possible. If the process was taken to its extreme and the design for one component was not started until a related component was finished, there could be the following problems:

- The time taken to produce an overall design would be unacceptably long;
- If problems were experienced with the design of the first component, it would be too late to go back and change the first component;
- No iteration (i.e. optimisation) is taking place;
- Any tasks which depend on the completion of a previous task will be subsequently delayed.

This is a situation where concurrent engineering is desirable. Concurrent engineering is described in section 2.2.10. It enables projects to be run concurrently, i.e. designing components in parallel. In its 'perfect' extreme, the design of a component which depends on the design of a previous one will be performed using the most up-to-date version of that previous component. However, in practice, this is rarely achieved since it often calls for an excessively large amount of redesign. Therefore, it is usual to perform the design in stages, with information on the latest design of all the components in a design being exchanged at set intervals.

Systems such as CATIA and CADDS 5 are useful when it comes to making sure that the most up-to-date version of structural components are available, since the information on the components which make up an aircraft is stored within a central data repository. This type of system also enables a situation where the project teams which make up the overall team are not co-located since the consistency between the teams is maintained through the database.

The idea of aircraft structures being designed using this system is generally given because the interface between each of the individual components should not change from day to day, and the structural interface must be sound for the design to work. However, the design of avionic systems is a little different to this. The structural considerations generally only concern the size and location of the avionic boxes, and it is generally possible to determine this in advance. In addition, the interfaces between the components supplied by one manufacturer and the rest of the aircraft are reasonably well defined, and will not change on a day-to-day level, though there may be some change during the lifetime of the project.

This brings about the idea of interfaces within teams, and interfaces between teams. Certainly, how a particular team accomplishes a specified goal is not important, as long as it is done in a cost effective manner, and all of the requirements are met. It is important for the components supplied by that team to fit in with the components supplied by other teams, and therefore the interfaces between components supplied by individual teams must be rigorously adhered to, even though the interfaces between components designed within a single team may vary.

The information flows generated within a project will generally vary in amount and content as the project progresses. This may be related to the NASA project phases described in section 2.4.2.

2.5.2 Information Flows Specific to the Project Described

The tasks represented in appendix A are those which make up the project. The lines connecting the tasks represent a flow of information. Since the project is generic, specific information for the flows has not been specified. However, the relationships between the tasks represent flows of information and these are contained within the appendix.

For example, the first flight cannot take place until the release for flight has been obtained. In this case, the information flow is a document confirming that the aircraft has been released for flight. Another example would be the hydraulic system definition. The preliminary hydraulic system cannot be defined until the aircraft configuration is available since the design is dependent on the number of control surfaces etc.

For the project described here, the information flows are designed to take account of the major flows between the manufacturers and subcontractors. They will not represent the individual contact which takes place on a day-to-day basis, nor will they represent the individual flows of information between project teams. This is assumed to be too detailed for the type of description considered here.

2.6 Project Management Discussion

Discussion of the study on management tools and the process model derived is contained within this section.

2.6.1 Project Management Tools

This section discusses the project management tools previously described, and highlights their usefulness in the aircraft design process.

Sequential Engineering

Sequential Engineering is the traditional approach to project management, however its weaknesses can clearly be seen when using its ideas to design an aircraft. Due to the parallel nature of aircraft development, a problem in one particular component will delay the whole aircraft.

In addition, problems found in a subcontractor may not be filtered back to the manufacturer since there may be fears of non-payment or other forms of recrimination.

Hence the use of sequential engineering methods should be avoided for large and complex products such as aircraft and their systems, especially with the requirement to specify the interface between the different components. This interface specification is alien to the concept of sequential engineering.

Simultaneous Engineering

Simultaneous engineering is directly applicable to aircraft manufacture since the benefits which it brings are necessary in today's competitive market. Simultaneous engineering is especially useful for large, complicated products since it brings the traceability required for this type of project. With an aircraft, the optimisation of the design is very important, and comments from people within the industry indicate that the new design tools which are being brought into practice are not used in the manner which they were originally intended, i.e. to quicken the design process, but to enable more configurations or possibilities to be considered, and therefore to produce a more optimised design.

In addition, complex and large products require a great deal of consideration in terms of how to manufacture them. The use of simultaneous engineering practices enables all aspects of the product design and development process to be considered during the design phase, and therefore the company can be confident that they can realise the designs with the least number of problems.

Concurrent Engineering

As seen in section 2.2.10, there are many different ways of describing concurrent engineering. However, among all the definitions, the following broad similarities may be obtained. Concurrent engineering is a concurrent design of products and their related processes, including all elements of the product life cycle. In other words, it is both product and process focused. Techniques such as QFD and many other are used within the Concurrent Engineering framework to ensure that the objectives of concurrent engineering are achieved.

In addition, it has been said that Concurrent Engineering is too rapid to be supported well by paper documents. Therefore there is the need to have some form of central repository in the same manner as a CAD system so that the latest requirements may be accessed as they are defined.

Concurrent engineering is very similar to concept to Simultaneous engineering, and the terms are often used in synonymously. Any differences depend on the definitions used for each methodology, but a difference, if one exists, may be expressed by stating that concurrent engineering focuses on cross-functional teams concerned with the complete product life cycle, whereas simultaneous engineering describes the simultaneous performance of all engineering functions within a company throughout the new product life cycle, though the effects which each produces are essentially the same, see sections 2.2.2 and 2.2.10.

Systems Engineering

As defined in section 2.2.3, systems engineering is fundamentally a methodology for the systematic approach to the specification, design, development and validation of any system. Systematic means that all participants follow the same orderly process, and there is design traceability from the top level to the lowest level. Therefore it is more a framework within which the other project management tools are used.

The systematic nature of systems engineering means that complex problems may be solved using the project management tools where these problems previously would not have been possible to solve, or would have resulted in long duration and costly solutions. Systematic also refers to the process of obtaining the finished product - it will not necessarily ensure that the product is the best one, but it will ensure that the design was carried out in a traceable and systematic manner. It therefore follows that if the process is performed correctly, using the design tools correctly, whether they be management or engineering tools, the product produced will be close to being optimised for the task in hand, with a minimum of expense and at the best obtainable performance.

Systems engineering is generally required by the US Department of Defense since the MIL-STD-499 must be adhered to, which is a means for ensuring that all of the contractors work in a systems engineering-like manner.

Quality / Total Quality Management

Quality is important for products due to the reasons described in section 2.2.4. It is important for companies therefore that quality issues are incorporated during the whole design process. Therefore the quality tools which exist are used to ensure that the process is carried out in a manner which ensures quality is considered, and this ‘quality in the process’ is used to ensure ‘quality in the product’.

Standards such as the ISO 9000 series are used to ensure that there is this ’quality in the process’, and many companies now require that their contractors are ISO 9000 approved. Total Quality Management is a tool which ensures that quality is present at all stages of the product design and development, and it also ensures that both ‘quality in the process’ and ‘quality in the product’ are addressed. TQM is also applied in a company wide manner, from the person on the shop floor, through to the design and development up to the highest management levels, and to succeed it requires a commitment from all of these levels. TQM was also mandated by the US DoD in 1988 to improve the quality of contracted systems, and to reduce costs and inefficiencies.

Quality Function Deployment

Quality Function Deployment is used to design quality into a system, and therefore it focuses on the ‘quality in the product’. It is a structured planning tool which may be used at all stages of a product design and development in order to determine the best solution to a wide range of problems.

It should be used throughout the design process, especially in the initial stages. It is particularly useful in the initial stages since it helps to ensure that the design of the product is in accordance with the customer needs, and it does this in the current market place, i.e. it is possible to take account of the competition. In addition to this, it also helps to identify possible problem areas and to pose solutions for them.

As stated in section 2.2.6, QFD may have helped to prevent the Ariane 5 incident (the destruction in flight of the 501 vehicle). By applying QFD to the design, it would have been determined that the piece of software which caused the problems was not necessary, and therefore should have been removed. It may be said that this accident was caused by a failure in the quality process. In addition, it has also been said that it was not possible to trace the decision tree which lead to the software being left in the avionic boxes in question, and no one person could be deemed accountable.

Statistical Process Control

Statistical Process Control is used to check for the behaviour of the production line, and to look at a sample of products for quality. Since it is based on statistics, and is used for production as opposed to design and development, it is not directly relevant to the aircraft design process.

Risk Management

A good risk management programme is necessary since it enables the risk inherent within a product to be minimised, and if problems exist, they enable them to be dealt with quickly and efficiently.

Risk management programmes do exist, and may be applied to specific systems within an aircraft. However, they require a certain amount of historical information which may not be available for the system under consideration. In addition, the systems tend to be very specialised, and due to their nature and the commercial marketplace, there may be little information available.

Therefore the use of risk management tools should be considered due to the inherent savings they produce in the event of them uncovering potential problems, but they may have inherent limitations which must be borne in mind.

2.6.2 The use of Computer Based Packages

This section details the use of computer based packages for the aircraft design and development process. Most of the case studies described in section 2.3 have used either CATIA or CADDS 5 in order to gain one or more of the following advantages:

- Improve the product lead time;
- Reduce the need for expensive mock-ups.;
- To improve the product quality;
- To produce a better design in less time;
- To cope with the complexities for very large projects.

These benefits speak for themselves, and the fact that all of the manufacturers have found the same advantages reflects on the software packages used. These packages require powerful computers, with many terminals and a large amount of storage capability. They also require a large amount of training to use. This highlights another problem with the use of these software packages - the company is dependent on being able to recruit well trained operators who also have a great deal of technical expertise. Investing in the workforce is therefore required to minimise the amount of time required to train operators when the system is first installed. In the event that experienced operators cannot be found the project may require some modifications to enable new personnel to be trained and operated. This is a risk which may be recognised at the risk identification level, and steps may be taken to minimise it. Finally, these tools need to be in place and ready to use before the start of the program.

2.6.3 The Team Arrangement

When analysing the case studies within chapter 2.3 it becomes clear that the product has been implemented with multi-functional teams. These teams enable the design to be conducted efficiently, but they also enabled all stages of the product life cycle to be considered at one time. The therefore form a vital part of the concurrent engineering process, since without these multi-functional teams, it is more difficult to produce a design which considers all aspects of the product life cycle. The comparison of sequential engineering methods with concurrent engineering methods highlights this (see sections 2.2.1 and 2.2.10).

These teams (Design/Built Teams) are often very flexible in their nature, with the personnel within each team changing as the project advances. These teams are also disassembled when the project is complete. Although this makes for a very flexible project, it means that the there needs to be quite a large amount of flexibility in the allocation of personnel, and this may cause problems in its own right.

Finally, the interfaces between teams need to be considered and defined early in the process so that the teams may work knowing how their designs need to interface with others. This process will be helped though the use of tools such as CATIA.

2.6.4 Aircraft Process Model Critical Path Discussion

This section considers the aircraft process model described in Appendix A. The critical path is explored, and suggestions made concerning improvements which may be made in the overall design process to reduce the time taken to design and develop the aircraft.

Analysis of the Critical Path

The first critical path is through the certification path, via the control law concept choice path. This means that the choice of control law concept must be made early as any delays will result in the project being delayed. If the decision concerning what control law concept to select is delayed then the certification process will also be delayed, resulting in the delay of the project.

The second critical path is through the certification path. This assumes that the control law concept for the aircraft has been chosen, since this will influence the certification process for the aircraft. In the event of any other major changes being made, the certification process will probably be required to restart, resulting in an overall program delay. As previously mentioned, the certification process is dependent on having a reasonable idea of the philosophies behind the aircraft, and if any of these are changed then the process must restart.

The third critical path, when both the certification and control law concept are ruled out of the critical path equation is through the aerodynamic testing, final control law design and hence through to the production Iron Bird Testing to certification. Therefore, if problems are experienced with the performance or reliability testing then they will result in the aircraft entering service late.

Firstly, these results demonstrate that the control law concept must ideally be known when the design process for the new aircraft is started, since the certification process requires this information, and without it, this process may be delayed.

Secondly, the next critical path from an avionics point of view is the testing of the production hardware and software. Indirectly, this feeds back to the aerodynamic modelling and testing required to produce the aerodynamic model for the aircraft. Hence if a sequential process is adopted, the aircraft certification will be delayed since the control laws cannot be designed until the aerodynamic model is available, and therefore the control law testing will be delayed.

A good aerodynamic model must also be identified early in the process. This will enable a preliminary control law design to be produced, and henceforth, the structure of the control laws may be defined. If there are any minor modifications in the control laws, either as a result of refinements in the aerodynamic model or the control laws as a result of flight test, the changes will be minor, and therefore the modifications will be approved with as little testing as possible.

Considering the process model in general, it can be seen that all of the tasks depend on the initial design, therefore this initial design needs to be correct. The modern tools such as QFD may be used to improve the initial design and therefore try to alleviate any problems which may exist. In addition, studies performed before the project is formally launched will enable the required knowledge to be acquired and will give a good grounding into the key technologies. Therefore when the project is launched, many of the possible questions will have already been addressed, and problem areas identified. This also shows the importance of generic research.

In order to reduce the program timescales, work needs to be carried out concurrently since the sequential process results in a drawn out design process. This requires the use of concurrent engineering techniques and processes such as Design/Build Teams. However, care must be taken that the extra time made available is used to reduce the overall time as opposed to enabling more design options to be considered. In addition, quality is also an important consideration here since ‘getting it right first time’ will drastically reduce the time and cost required for rework and redesign.

The testing process analysis demonstrates that the aerodynamic data testing is important since time is required to validate the aerodynamic model and solve any subsequent problems in the control law designs if any unexpected characteristics are found in the aerodynamic properties. Problems found here will take time to correct and therefore this aerodynamic testing should ideally be performed early on in the flight test programme. The performance testing may not have such a critical role since little may be able to be done concerning performance shortfalls at this stage, and the production or verification of flight manual data simply takes time with likelihood of a requirement to make modifications to the aircraft or retest components. This reflects the emphasis required for modern flight control systems where the flight test program is designed around the reliability testing as opposed to the performance verification.

Limitations

This project is subject to the following limitations. Firstly the data is based on comment from industry experts due to time constraints and therefore may be a little subjective. Secondly, as a result of the detail required to model the use of concurrent engineering, further benefits may be realised from the correct application of concurrent engineering.

2.7 Summary Conclusions

The following conclusions may be made:

- The initial design process is important since much of the initial costs and design decisions are made at the early stage and therefore a high proportion of the costs are determined as well;

- Quality must be addressed from an early stage;
- Modern project management tools may be used to good effect, but they must be used correctly and the organisation must want to accept these changes;
- The TQM methodologies combined with QFD combine to produce the right product at the right price on time.

3 Classical Aircraft Dynamics and Response Characteristics

This Chapter details the theoretical issues associated with this work. Firstly, the classical aircraft response is considered since this is generally the starting point for all fly-by-wire design work. Secondly, some of the unconventional response types are considered, and the differences between these and those of a classical aircraft are highlighted. Finally, frequency response characteristics in the form of bode asymptote plots for both the classical and unconventional response characteristics are considered.

For the purposes of this work, the following definitions are required. As stated earlier, a control law is the software code contained within a flight control system to give the aircraft specified properties. Control laws are often named after their response characteristics, so a pitch rate control law has pitch rate-like characteristics (to be considered later). The response characteristics are the specific characteristics which a given aircraft / flight control system may have. Certain response characteristics may be referred to as a response type, such as a pitch rate response type.

3.1 Classical Aircraft Response Characteristics

This section describes the nature of the longitudinal response characteristics of a classical aircraft. As most of the current transport aircraft do not have fly-by-wire systems they may be classified as having 'classical' response characteristics. A simple pitch damper will still have 'classical' response characteristics as the pitch damper is present to improve the aircraft's response characteristics and not to significantly change them.

A classical aircraft may be described as having pitch rate demand characteristics in the short term and angle of attack demand characteristics in the long term. Therefore, if the pilot makes a pitch command, he is demanding pitch rate in the short term in the first few seconds or so, and is demanding an angle of attack in the long term. The angle of attack, pitch attitude and flight path angle responses to an elevator step input may be seen in figure 3.1 for the constant speed approximation and 3.2 for the full order response. Note that the significant differences exist in the long term (after 3 to 5 seconds) and the responses are essentially identical in the short term. More information may be obtained from the Cook [45] and Field [4] references.

This relationship holds for both the full order and reduced order or constant speed approximation. The constant speed approximation assumes that the airspeed is constant throughout the response and hence only considers the short term mode. The full order response considers both the short term and long term characteristics, i.e. both the short and long term modes are considered. The describing transfer functions for the constant speed approximation are commonly represented as follows for pitch attitude:

$$\frac{\theta}{\delta_e} = \frac{K_\theta(s + \frac{1}{T_{\theta_2}})}{s[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2]} \tag{3.1}$$

for pitch rate

$$\frac{q}{\delta_e} = \frac{K_\theta(s + \frac{1}{T_{\theta_2}})}{[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2]} \tag{3.2}$$

for flight path angle

$$\frac{\gamma}{\delta_e} = \frac{K_\gamma}{s[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2]} \tag{3.3}$$

and for angle of attack

$$\frac{\alpha}{\delta_e} = \frac{K_\alpha}{[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2]} \tag{3.4}$$

These equations demonstrate that for the constant speed approximation, a classical aircraft has both angle of attack and pitch rate demand characteristics, since the steady state pitch rate and the steady state angle of attack for a classical aircraft are both constant. The response to a step input may be found on figure 3.1 for these transfer functions.

The situation is a little more complex for the full order equations as a long term mode is present as well as a short term mode. The response characteristics for the full order approximation are shown in figure 3.2 and the describing transfer functions for the full order mode are commonly represented as follows for pitch attitude:

$$\frac{\theta}{\delta_e} = \frac{K_\theta(s + \frac{1}{T_{\theta_1}})(s + \frac{1}{T_{\theta_2}})}{[s^2 + 2\zeta_{ph}\omega_{ph}s + \omega_{ph}^2][s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2]} \tag{3.5}$$

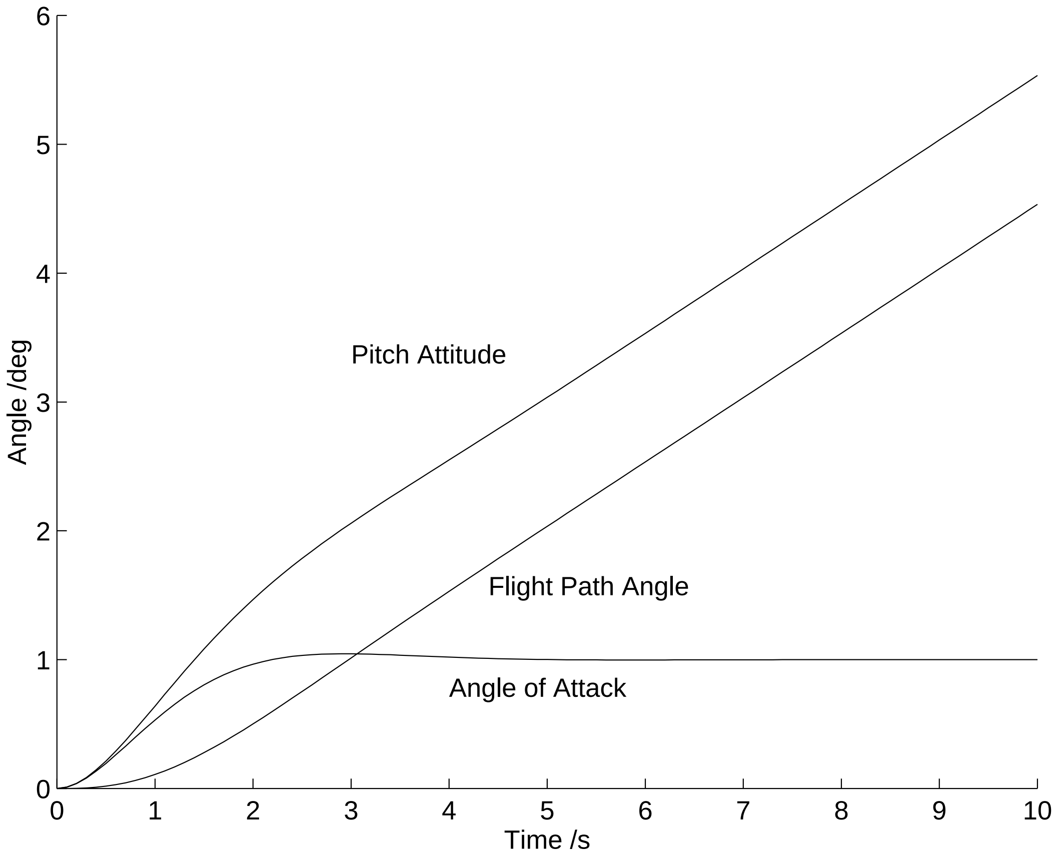


Figure 3.1: Constant Speed Approximation Classical Aircraft Responses to Step Stick Force Input

for flight path angle

$$\frac{\gamma}{\delta_e} = \frac{K_\gamma(s + \frac{1}{T_{\gamma_1}})(s + \frac{1}{T_{\gamma_2}})(s + \frac{1}{T_{\gamma_3}})}{[s^2 + 2\zeta_{ph}\omega_{ph}s + \omega_{ph}^2][s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2]} \tag{3.6}$$

and for angle of attack

$$\frac{\alpha}{\delta_e} = \frac{K_\alpha(s + \frac{1}{T_\alpha})[s^2 + 2\zeta_a\omega_a s + \omega_a^2]}{[s^2 + 2\zeta_{ph}\omega_{ph}s + \omega_{ph}^2][s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2]} \tag{3.7}$$

The angle of attack transfer function (equation 3.7) has a numerator complex pair which cancel with the phugoid mode complex pair for the ‘perfect’ classical aircraft, and hence the long term phugoid mode does not influence the angle of attack response. However, there is a residue from this phugoid mode in both the pitch attitude and flight path angle transfer functions. These oscillations have a long period and are lightly damped. The airspeed is also changing during this long term response, and the pitch attitude and flight path angle oscillations will disappear as the airspeed stabilises at a steady value.

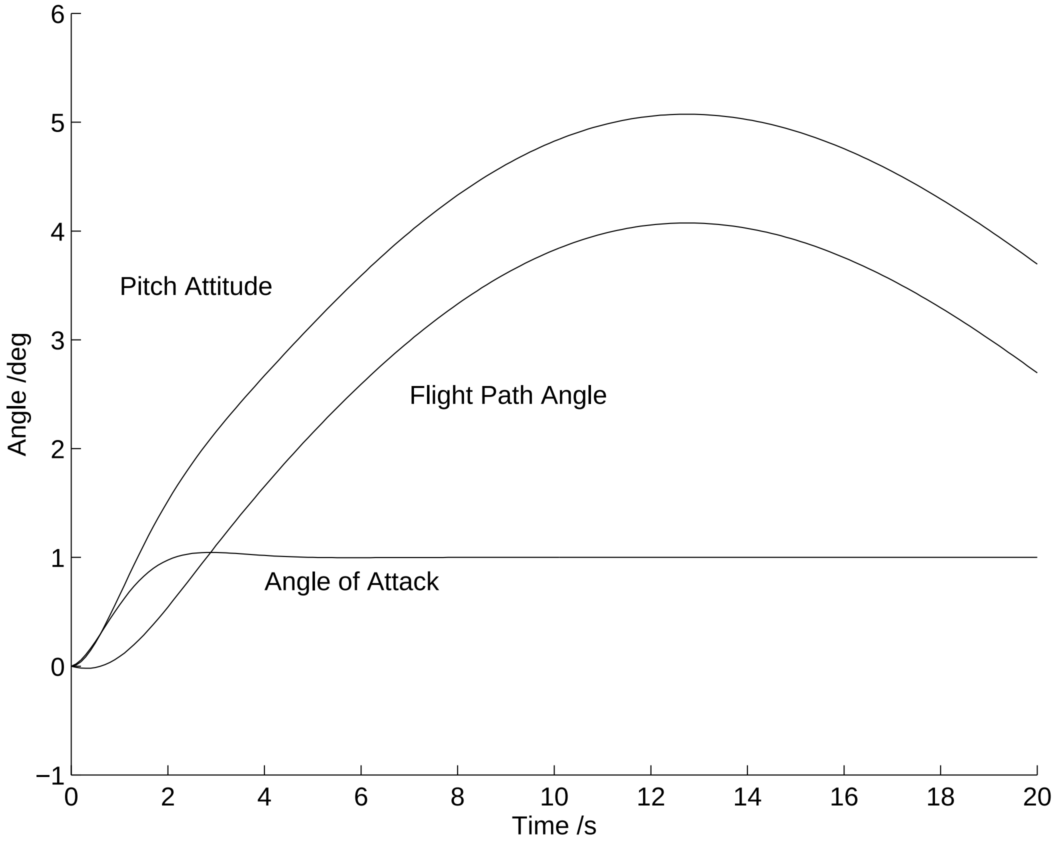


Figure 3.2: Full Order Classical Aircraft Responses

Since a pilot will generally attempt to maintain airspeed when flying an aircraft, the constant speed approximation is a useful approximation to the response characteristics of an aircraft. It can also be seen that there are a number of zeros included with both the angle of attack, pitch attitude and flight path angle transfer functions. Of these, the important zero in the pitch attitude transfer function is the $\frac{1}{T_{\theta_2}}$ as this connects the aircraft flight path response to the pitch attitude response. It is considered in section 4.4.

The $\frac{1}{T_{\gamma_1}}$ zero in the flight path angle transfer function determines whether the aircraft is on the front or back side of the drag curve. This is also important as problems may result when the aircraft is flown on the backside of the drag curve (where the drag increases as the airspeed decreases and vice versa, which can cause flight path control problems). It is generally negative (i.e. left of the imaginary axis on the s-plane) for most aircraft resulting in front side operation.

3.2 The Series Pilot Model

The series pilot model states how a pilot behaves for a conventional classical aircraft in a precision flight path control task and is described within references [4] and [46]. The model is shown in figure 3.3 and consists of two loops - an inner pitch attitude loop and an outer flight path loop.

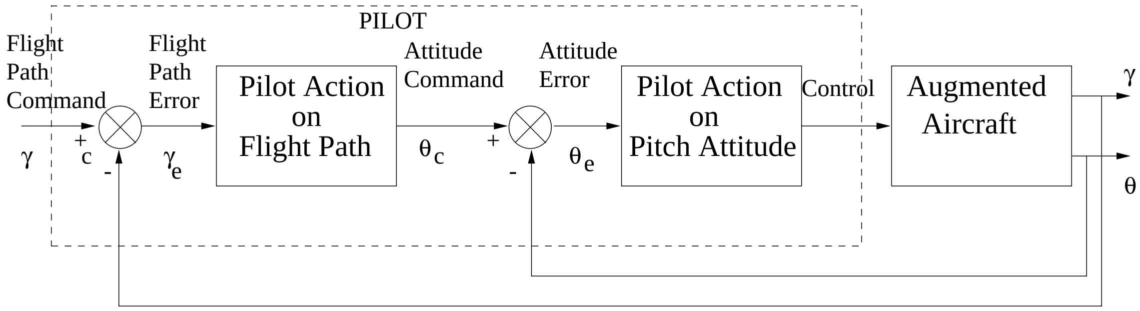


Figure 3.3: The Series Pilot Model

The series model is based on the fact that the flight path angle response lags the pitch attitude (see figures 3.1 and 3.2) and these lags in the flight path angle response make it difficult for the pilot to control the flight path response tightly whereas he can control the pitch attitude relatively easily. Therefore he uses the pitch attitude as a surrogate for flight path angle.

In order to reduce the flight path error to zero, the pilot will decide on a pitch attitude and attempt to maintain it. He will then maintain the pitch attitude at that value while monitoring the flight path angle. When a change is required to the flight path angle or if the flight path angle is not quite what the pilot desires, the pilot uses his knowledge of the aircraft to determine the new pitch attitude which he believes will give this flight path angle and he will then maintain this new pitch attitude. Any fine changes to flight path may then be made through fine pitch attitude changes. There will, of course, be throttle inputs throughout the process to control the airspeed.

This is the standard longitudinal control technique which has been taught to pilots for a considerable period of time, since the problems of flight path delay preclude direct control of the flight path angle despite the fact that the pilot is trying to control the flight path directly. Therefore an aircraft which has good attitude dynamics and a predictable pitch attitude / flight path relationship will be deemed to have good flying qualities as the pilot will find it relatively easy to maintain the desired pitch attitude and also to determine what pitch attitude is required to give the desired flight path angle. This technique of controlling flight path through pitch attitude applies throughout the flight envelope.

Modern flight control systems can modify an aircraft's behaviour so that it no longer responds in a conventional or classical manner. These unconventional responses are defined as responses which do not have classical characteristics, i.e. pitch rate demand characteristics in the short term and angle of attack demand characteristics in the long term. The common unconventional response characteristics are described within the next section. A different piloting technique may now be required since the pilot may be able to control the flight path directly and therefore the pilot may not have to close the inner pitch attitude loop as required by the series pilot model.

3.3 Unconventional Response Characteristics

The unconventional response characteristics considered for the purposes of this work are listed as follows:

- Pitch rate response characteristics (used by the McDonnell Douglas C-17), where the pilot demands pitch rate, and the aircraft maintains pitch attitude with no pilot input;
- Normal acceleration response characteristics (used by the Airbus A320), where the pilot demands normal acceleration or flight path rate, and the aircraft will maintain the flight path angle in the presence of no pilot input.
- A C* control law, which has pitch rate-like characteristics at approach airspeeds and normal acceleration like characteristics up and away. C* may also be used where any blend of normal acceleration and pitch rate is considered;

The above non-conventional response types may be called 'rate demand' response characteristics since the pilot's stick is making demands which are giving response characteristics in the short term similar to those of the pitch rate response characteristic. Hence the aircraft will appear similar to a classical aircraft since that also has rate-like characteristics in the short term. There are other demand characteristics such as angle demand characteristics, where the pilot is essentially demanding pitch attitude or flight path angle. These are sometimes used for specialist applications, such as air-to-air refuelling or Low Altitude Parachute Extraction. However, although they may be suitable for the flare portion of the landing task, they are generally deemed to be unsuitable for the final approach task [4], and therefore have not been considered as a part of this programme.

In addition to these response types, the aircraft designed as a part of this study may also have either airspeed or angle of attack stability. Airspeed stability is where the pilot trims the aircraft to a specified airspeed, and the aircraft will try to maintain that airspeed in the presence of external disturbances. Angle of attack stability is where the aircraft will attempt to maintain angle of attack in the presence of external disturbances, as a classical aircraft would. The difference between these aircraft and a classical aircraft is that the aircraft here may have significantly different short term characteristics, but still have the same long term characteristics as the classical aircraft.

3.3.1 Pitch Rate Response Characteristics

A pitch rate response characteristic is a response characteristic where the pilot demands pitch rate both in the short term and long term in an attempt to give good pitch control throughout the flight envelope. Therefore it is similar to a classical aircraft in the short term, but different in the long term as the pilot will still be able to demand pitch rate. The response to a step input may be seen in figure 3.4.

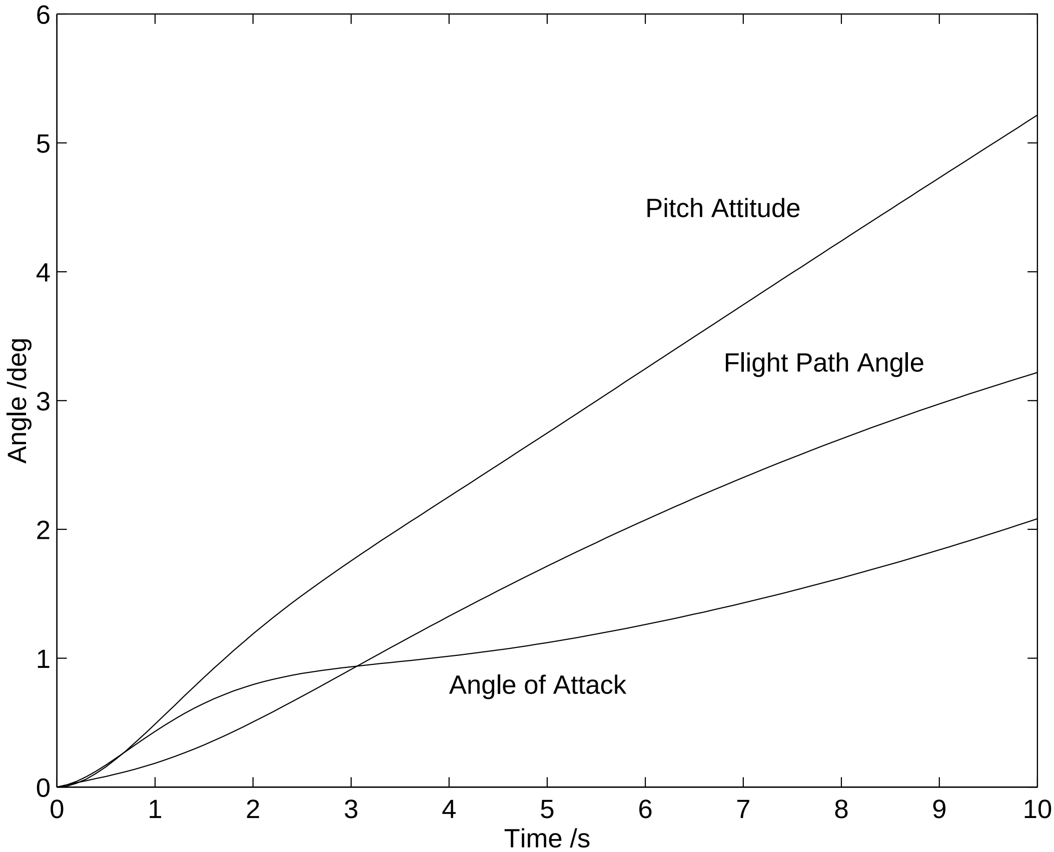


Figure 3.4: Pitch Rate Step Response Characteristic

Pitch rate command laws originated in fighter aircraft since they provide excellent pitch pointing characteristics by their nature, and they are also semi-conventional, since a classical aircraft behaves in a pitch rate manner in the short term. Pitch rate control laws generally form the basis of the low speed control laws for current fighter aircraft, with some additional elements to artificially induce speed stability.

In addition, the McDonnell Douglas C-17 uses a pitch rate command system as its 'frontside control law', with the backside control law being a conventional angle of attack command system. In addition, the C* response characteristic has pitch rate-like response characteristics at low airspeeds.

3.3.2 Normal Acceleration Response Characteristics

A normal acceleration control law is where the pilot demands a specified load factor or flight path rate (the two are proportional to each other). This type of response characteristic may also be referred to as a flight path rate response characteristic. The response to a step input may be seen in figure 3.5.

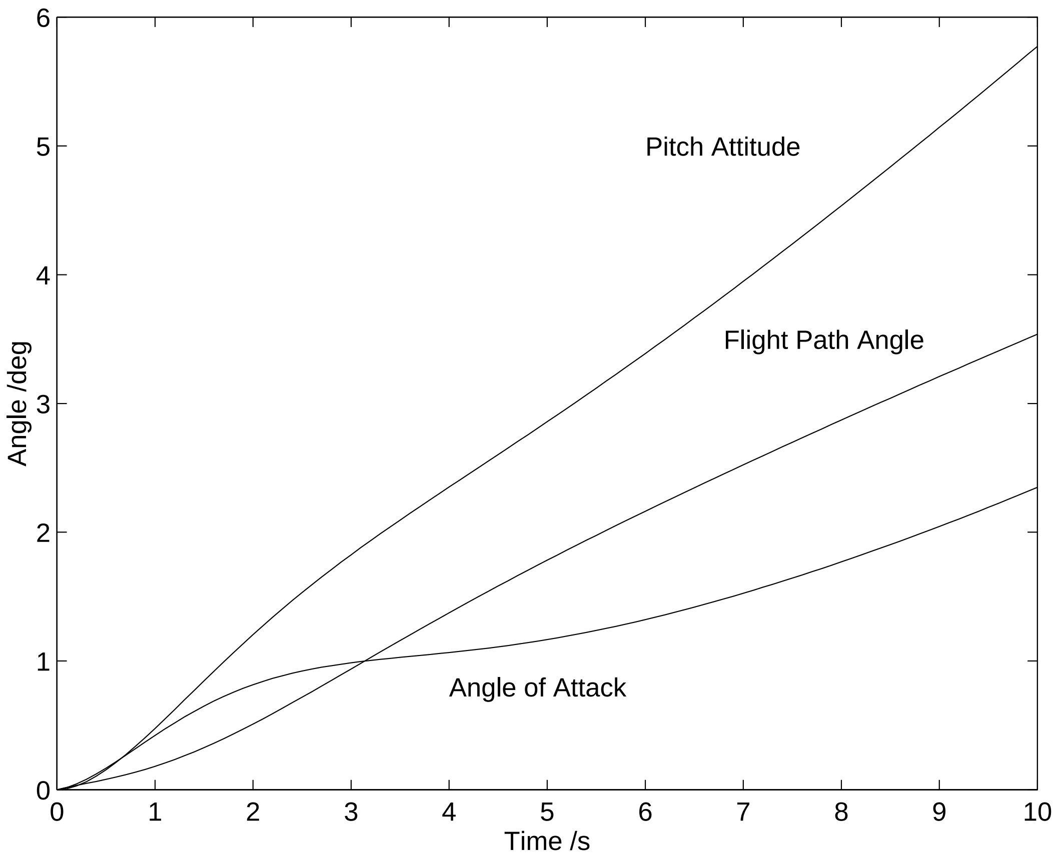


Figure 3.5: Normal Acceleration Step Response Characteristic

This type of control law or a derivation of it is generally used by modern transport aircraft such as the Boeing 777 [47] and Airbus A320, A330 and A340 [48] as their primary flight control law as the flight path rate response characteristics give good control of flight path, which is of paramount importance to a civil aircraft pilot.

3.3.3 C* Response Characteristics

C* was initially developed as a time domain handling qualities parameter by Boeing, see reference [49]. It is defined as the weighted sum of the aircraft pitch rate and normal acceleration parameters, where K_q is a constant. This may be seen in equation 3.8.

$$C^* = N_Z + K_q q \tag{3.8}$$

A control law may be derived from the above equation with the C* parameter being the controlled parameter. The C* control law was initially designed as a fighter control law for a pitch pointing task. It is characterised by the fact that the pilot demands a blend of pitch rate and normal acceleration. This blend is determined by a gain, represented here as K_q. At low airspeeds, the C* control law behaves in a pitch rate manner, and at high airspeeds, it behaves in a normal acceleration manner.

C* can be considered as a blend of the numerators of the normal acceleration and pitch rate transfer functions, depending on the precise value of the constant K_q. For the law to have largely pitch rate characteristics, the value for K_q generally needs to be large and for normal acceleration-like characteristics, it needs to be considerably smaller.

It has been said that the Airbus A320, A330 and A340 use C* as their primary control law [48]. This is not pure C* as proposed by Malcom, Tobie and Elliot which has a specific Pitch Rate / Normal Acceleration blend [49], but a different blend of the pitch rate and normal acceleration parameters. In practice, any blend of normal acceleration and pitch rate is generally referred to as having C* response characteristics. The Airbus aircraft have manoeuvre demand characteristics, where the pilot's pitch inceptor demands normal acceleration or flight path rate, and will have characteristics similar to those of the normal acceleration control laws designed here.

3.4 Static Margin and Manoeuvre Margin Description

Static stability and manoeuvre stability are two fundamental properties which apply to classical aircraft.

Static stability determines whether an aircraft returns to a steady state angle of attack, and static margin is a measure of this. A pilot will generally trim an aircraft to remove any stick forces, and this gives a trimmed angle of attack to which the aircraft will attempt to return if the aircraft is stable. The pilot will generally see this as the aircraft returning to a trimmed airspeed, or the airspeed which corresponds to the trimmed angle of attack. If the aircraft positively returns to this trimmed angle of attack the static margin is said to be positive, if the aircraft makes no attempt to return to, or diverges from, this angle of attack then the static margin is neutral, and if the aircraft positively diverges from this angle of attack, the static margin is said to be negative. Not all aircraft have a positive static margin, but this does not generally pose a problem, even though the pilot can sense whether an aircraft has positive static margin.

Manoeuvre stability relates to how the pilot's stick demands correspond to the aircraft normal acceleration response and manoeuvre margin is again a measure of this. If the aircraft always gives a 'g' demand proportional to the stick displacement then the manoeuvre margin is positive. If the 'g' demand is generally unaffected by the stick demand then the manoeuvre margin is neutral, and if the 'g' demand is independent of the stick input, the manoeuvre margin is negative. All aircraft have a positive manoeuvre margin from the pilot's point-of-view; otherwise the aircraft would probably be unflyable. Manoeuvre margin is very strongly related to the Control Anticipation Parameter flying qualities criterion and this criterion is considered in more detail in a later section.

For a classical aircraft, the difference between the static margin and manoeuvre margin is more or less fixed. As the centre of gravity position is moved aft, the static margin and manoeuvre margin both decrease such that the static margin may become zero while the manoeuvre margin is still positive. The following equation may be shown to represent this [50]:

$$Manoeuvre\ Margin \approx Static\ Margin + Pitch\ Damping \tag{3.9}$$

An aircraft with high pitch damping will tend to resist disturbances in pitch attitude while an aircraft with low pitch damping will not.

For an unconventional response type, the classical relationship between static and manoeuvre margin is modified. For a pitch rate demand system, the static stability of the aircraft is zero, i.e. the aircraft will not try and return to a trimmed angle of attack. The pilot can perceive this through the nature of the aircraft response. However, he can still see an effective 'manoeuvre margin' as he will still be able to control the normal acceleration response. The lack of contribution of effective static margin to the effective manoeuvre margin, assuming classical aircraft dynamics is therefore made up by pitch damping. Pitch damping is very high for a pitch rate response characteristic as this type of response characteristic attempts to maintain zero pitch rate in the presence of disturbances.

It can also be shown that the short period mode determines the manoeuvre margin or manoeuvre stability characteristics of a classical aircraft [50]. Therefore changes to the short period mode characteristics will give changes to the manoeuvre stability characteristics.

Following on from this, it is proposed that a classical response characteristic in this context is also considered to be one where the classical relationship between static and manoeuvre stability is maintained.

3.5 Frequency Response Characteristics

Use of often made of Bode asymptote plots when considering the characteristics of different response types, and some of these plots are presented here. These plots have been derived from the control laws designed using proportional-plus-integral controller design methods, considered later in this document. The following items of information are also required:

- The crossover region (or region of piloted crossover) is the frequency band within which a pilot will generally be controlling the aircraft if he is working in a closed loop manner. It is generally accepted to be between 0.7 and 4 rad/s, i.e. from above $1/T_{\theta_2}$ which is around 0.5 rad/s to frequencies above the short period mode natural frequency;
- A gain term will affect the bode response gain, but not the phase;
- A single pole or zero is represented by $\frac{1}{T}$. A complex pair of poles is represented by ω;
- A zero in the transfer function will change the bode magnitude slope by 20 dB/decade and advance the phase by 90 degrees;
- A pole in the transfer function will change the bode magnitude slope by -20 dB/decade and retard the phase by 90 degrees. A complex pair of roots will change the bode magnitude slope by -40 dB/decade and retard the phase by 180 degrees.

The terminology used when expressing response characteristics is explained here. K, K/s and K/s^2 response characteristics are described in more detail. The K, K/s and K/s^2 responses to a step input are shown on figure 3.6, with K being unity in each case.

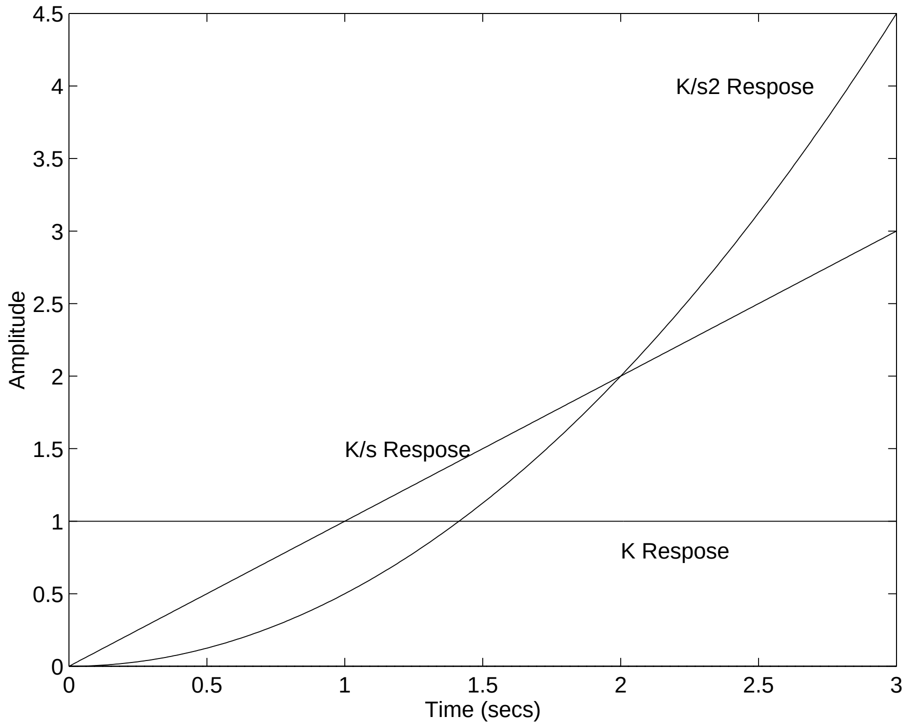


Figure 3.6: K, K/s and K/s^2 Responses to a Step Input

A K response is where the output is directly proportional to the input. In this case, the frequency domain relationship between output and input will show no phase loss, and the magnitude of the output in relation to the input will be determined by the magnitude of K.

A K/s response is where the relationship between the output and input has integrator-like properties. Therefore a step input will produce a steadily increasing output. The rate of increase is determined by the magnitude of K. The frequency domain relationship between the output and input for a K/s response has a magnitude change of -20 dB/Dec and a phase difference of -90 degrees over all frequencies.

A pure K/s^2 response in a particular parameter is where that parameter will increase with a constant acceleration to a step input. This is effectively the same as having two transfer function poles at the s-plane origin (or two free integrators), and therefore low frequency phase of -180 degrees. The frequency domain relationship between output and input are characterised by a decreasing bode plot gain of -40 dB/Dec, and a phase difference of -180 degrees. The magnitude of the acceleration is proportional to K.

3.5.1 Frequency Response Characteristic for a Classical Aircraft

This classical aircraft frequency response can be seen on figure 3.7. This response characteristic has K properties in pitch attitude for frequencies between $1/T_{\theta_2}$ and the short period mode natural frequency, giving good closed loop control of attitude. The classical aircraft also has a K/s response in flight path angle from frequencies below $1/T_{\theta_2}$ to the short period mode natural frequency. At low frequencies the pitch attitude response is also K-like which should give the pilot good open loop control of pitch attitude.

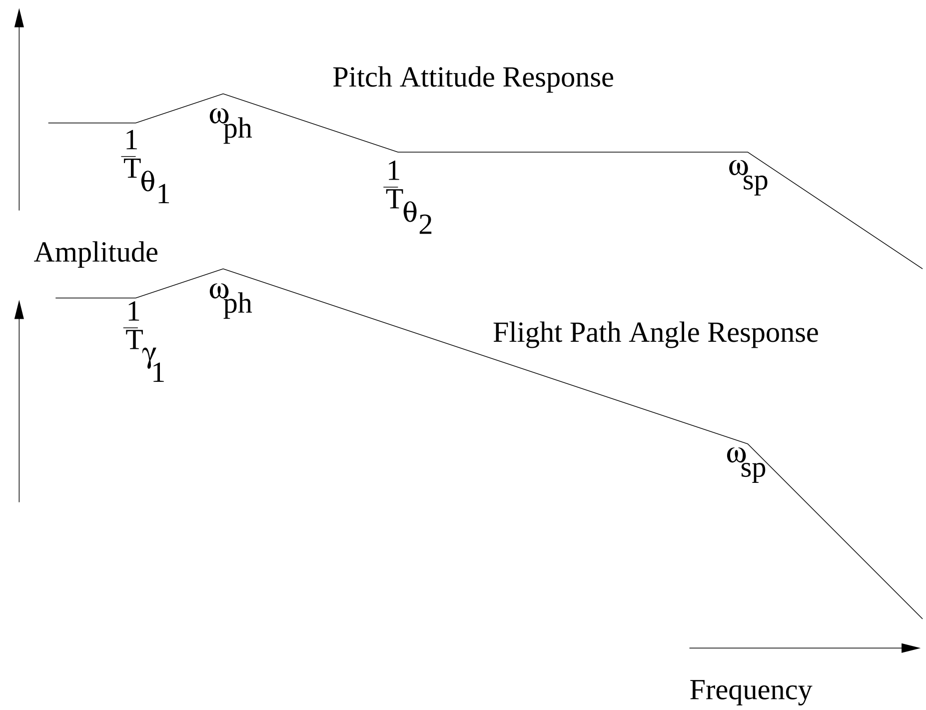


Figure 3.7: Frequency Response Characteristic for a Classical Aircraft Response

3.5.2 Frequency Response Characteristic for Unconventional Response Types

The pitch rate response type frequency response characteristics can be seen in figure 3.8 and the pitch rate response with speed stability in figure 3.9. It can be seen in both figures that both response characteristics have K type properties in pitch attitude, with K/s properties in flight path angle in the crossover region. The difference due to the speed stability is reflected in the lower frequency end of the bode plot (i.e. below the $1/T_{\theta_2}$ frequency), where the two single poles combine to make a slow second order mode.

The normal acceleration response bode plot can be seen in figure 3.10, with the normal acceleration response with speed stability in figure 3.11. As with the pitch rate responses, it can be seen in both figures that both response characteristics have K-type properties in pitch attitude, with K/s properties in flight path angle.

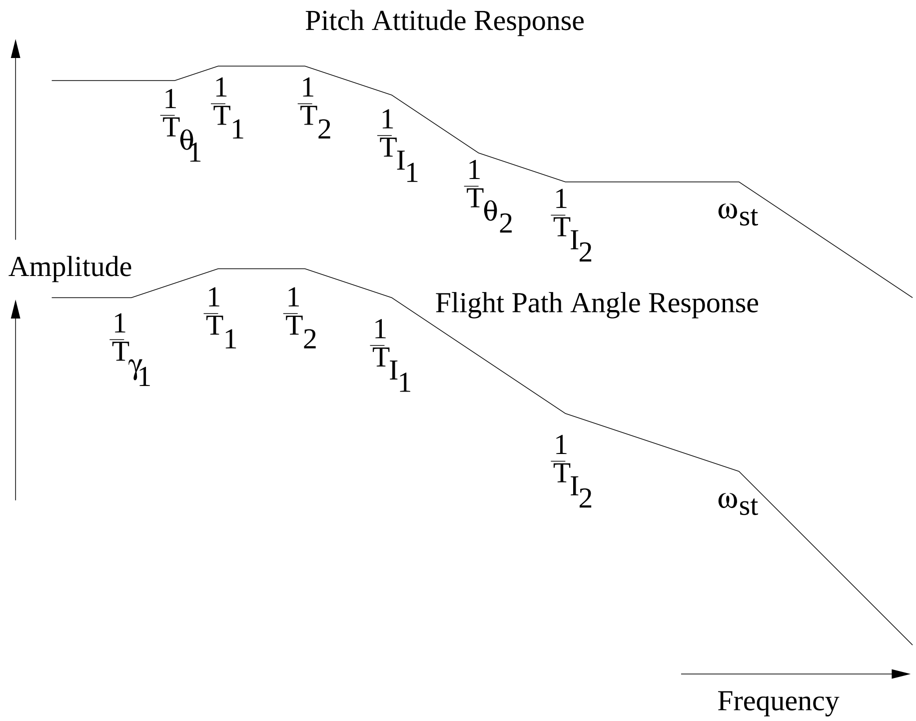


Figure 3.8: Frequency Response Characteristic for a Pitch Rate Response Type

From the unconventional response types, note the phase compensation in the crossover region for the normal acceleration response (see figure 3.10). In addition, all of the pitch attitude responses have K type characteristics from frequencies at approximately $1/T_{\theta_2}$ to the short term mode natural frequency. All the response characteristics also have K/s characteristics in flight path from below $1/T_{\theta_2}$ frequencies to the short term mode natural frequency.

The pitch rate control law has two slow poles around the normal phugoid natural frequency. When speed stability is added, these two poles combine to form a second order mode, which then has the desired characteristics for the long term mode. The phase compensation is also in the crossover region for both the normal acceleration and pitch rate control laws. For the normal acceleration control law, one pole is at a very low frequency, and therefore there is a slightly different arrangement of poles and zeros. This gives problems when introducing speed stability since the two poles have a large frequency difference between them.

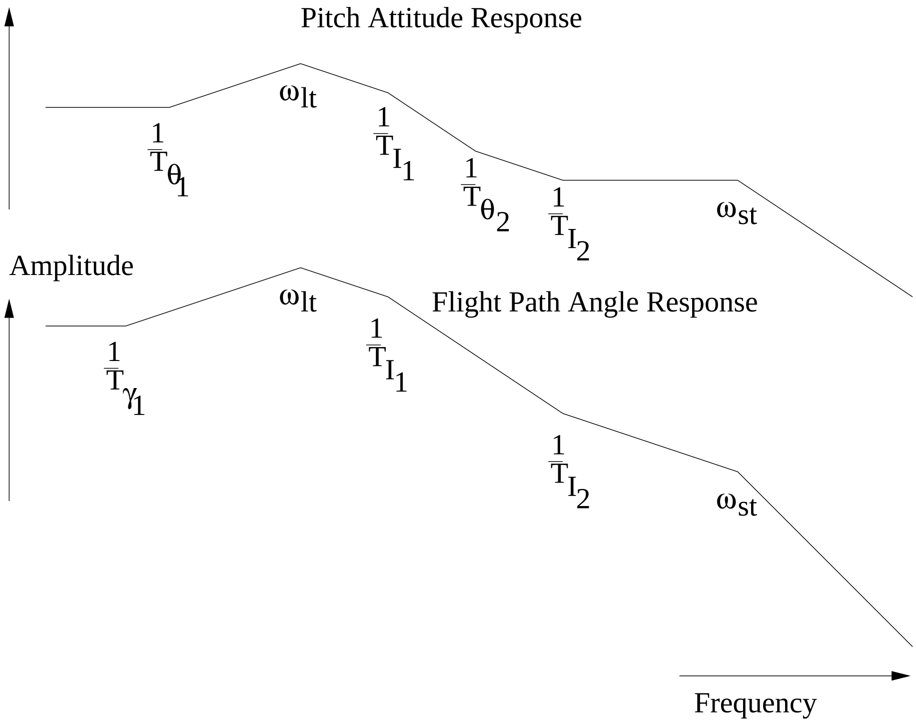


Figure 3.9: Frequency Response Characteristic for a Pitch Rate with Airspeed Stability Response Type

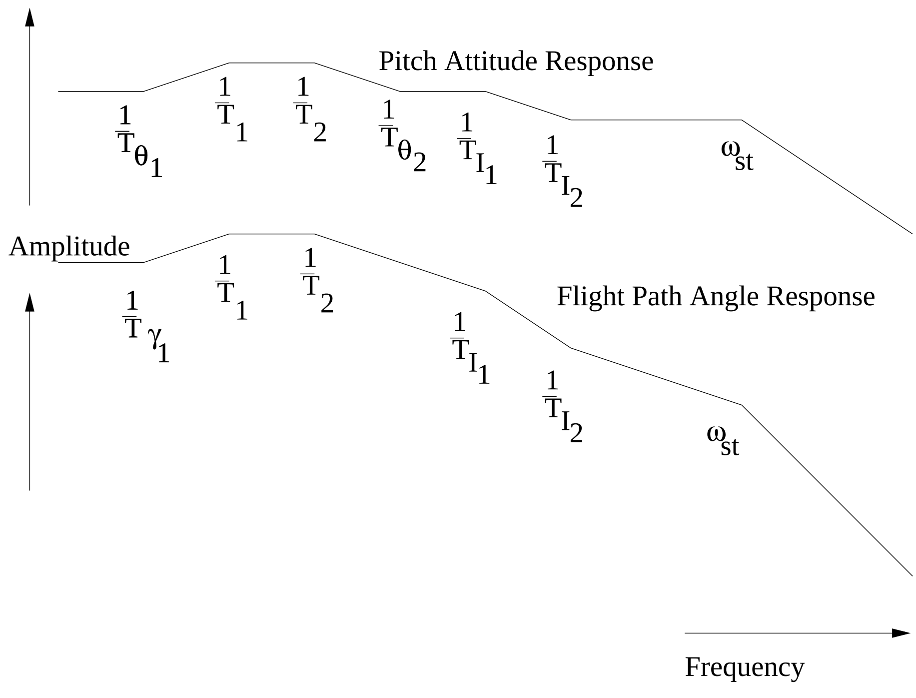


Figure 3.10: Frequency Response Characteristic for a Normal Acceleration Response Type

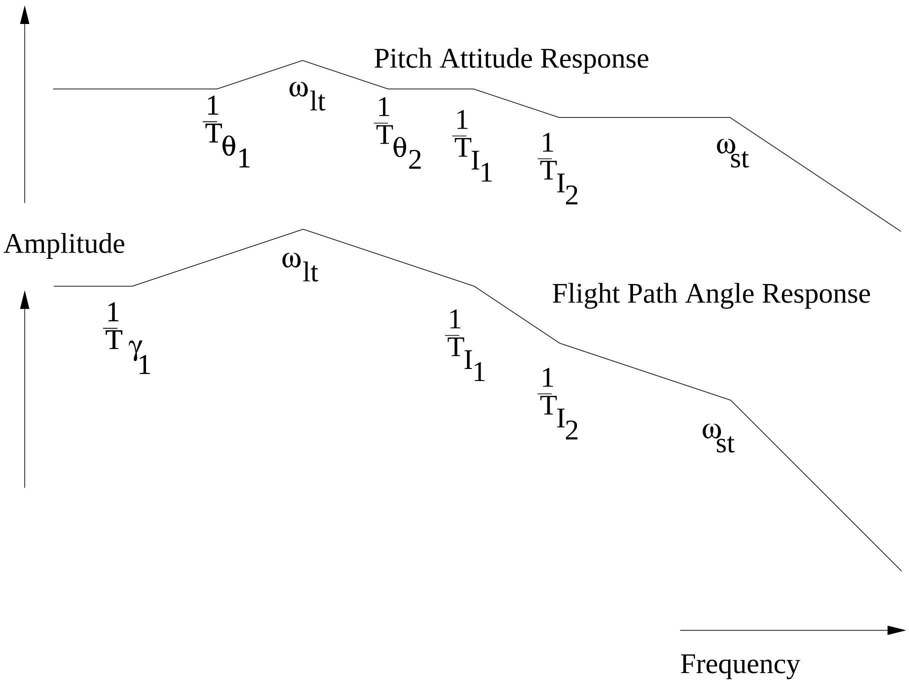


Figure 3.11: Frequency Response Characteristic for a Normal Acceleration with Airspeed Stability Response Type

4 Flying Qualities Criteria, Airworthiness Requirements and the Associated Pilot Rating Scales

In order to be able to design and assess the flying and handling qualities of aircraft, criteria have been developed so that this task is made easier. However the use of such criteria is not as simple as it may initially seem. Due to the fact that most criteria are essentially based on experimental data, they are only relevant in the context in which the data was obtained, and must therefore be treated accordingly. This chapter briefly describes those criteria which have been found to be useful, and also considers their validity for the evaluations considered in this work.

Much has been written on criteria and their comparison. Therefore the number of criteria considered will be limited to those deemed relevant. For a fuller explanation of other criteria which have also been considered, see reference [51] for longitudinal criteria and [52] for lateral criteria. The flying qualities criteria considered as a part of this work are listed in table 4.1.

Before this work is presented, the aircraft types and categories require presenting. The following are aircraft classes, or types of aircraft and are obtained from reference [53].

- **Class I**: Small light aircraft such as light utility and primary training aircraft;
- **Class II**: Medium weight, low to medium manoeuvrability aircraft such as tactical bombers, heavy utility or reconnaissance aircraft;
- **Class III**: Large, heavy, low to medium manoeuvrability aircraft such as heavy bombers, heavy transport and heavy cargo aircraft or tankers;
- **Class IV**: High manoeuvrability aircraft such as fighters or interceptors, attack and tactical reconnaissance aircraft.

The aircraft under evaluation for this study is a transport aircraft and is commonly referred to as class III. In addition, flight phase categories are referred to, and are classified as:

- **Category A**: Non-terminal flight phases which require rapid manoeuvring, precision tracking or precision flight path control such as air-to-air combat or flight refuelling;

Criterion	Description
Control Anticipation Parameter	Places limits on the short period frequency or manoeuvre margin of the aircraft
Low Order Equivalent Systems	LOES was not used for this work, but performs frequency matches to obtain a low order system with an equivalent frequency response of a high order system over a specific frequency range
Gibson's Dropback	Places limits on the characteristics of the pitch attitude response to a step input
Sturmer's Pitch Sensitivity	Places limits on the pitch rate sensitivity
Gibson's Attitude Frequency Response	Places boundaries on the Nichols plot of pitch attitude
Bandwidth	Places limits on the gain and phase margins for the pitch attitude and flight path angle responses
Gibson's Phase Rate	Specifies the maximum rate of change of pitch attitude phase with frequency at the crossover point
Neal-Smith	Uses a pilot model to give compensation to obtain a specific pitch attitude frequency response characteristic, and places limits on the characteristics of the required compensation

Table 4.1: The Flying Qualities Criteria Considered for this Work

- **Category B**: Non-terminal flight phases which are accomplished through gradual manoeuvres without rapid manoeuvring though precision flight path control may be required such as cruise and loiter and climb/descent;
- **Category C**: Terminal flight phases which are accomplished through gradual manoeuvres and usually require precision flight path control such as take-off, approach and landing.

The evaluations performed for this work are either Cat A or Cat C. Finally, flying qualities Levels are used and require clarification. They may be classified as:

- **Level 1**: Flying qualities clearly adequate for the mission flight phase;
- **Level 2**: Flying qualities adequate to accomplish the mission flight phase but increase in pilot workload and/or decrease in mission effectiveness exists;
- **Level 3**: Flying qualities are such that the aircraft may be controlled safely but excessive increase in pilot workload and/or inadequate mission effectiveness.

Cat A flight phases may be terminated safely and Cat B and C flight phases can be completed.

4.1 Flying Qualities Rating Scales

Before the criteria used for this work are described, the pilot rating scales, which are used to assess the flying qualities are presented.

4.1.1 Cooper Harper Flying Qualities Rating Scale

The Cooper Harper flying qualities rating scale is generally used to rate the flying qualities for a particular aircraft performing a particular task.

It is a flying qualities scale that measures both task performance, and workload. The pilot is asked to assess his actual performance compared to desired or adequate performance levels. Once the performance level has been decided, a further refinement of the flying qualities rating is made by the pilot qualitatively assessing his workload.

The flying qualities ratings produced are for a particular aircraft being flown for a particular task, and substantially different ratings may be found for a different task. The Cooper Harper Scale may be found in figure 4.1. It is generally accepted that Cooper Harper ratings of 1 to 3 correspond to Level 1 flying qualities, Cooper Harper ratings of 4 to 6 correspond to Level 2 flying qualities and Cooper Harper ratings of 7 to 9 correspond to Level 3 flying qualities. A Cooper Harper rating of 10 corresponds to flying qualities worse than Level 3.

4.1.2 Workload

Workload is of fundamental importance to aircraft flying qualities. Workload is thought to be a multi-dimensional construct combining the demand imposed on the pilot as he attempts to achieve the flight objective and the momentary capacity of the pilot to meet these demands [54].

Roscoe and Ellis proposed a definition for workload, which is modified slightly from Cooper and Harper's definition as ' Workload is the integration of mental and physical effort required to satisfy the perceived demands of a specified flight task.'

With the advent of single crew aircraft, pilot workload is of vital importance since if

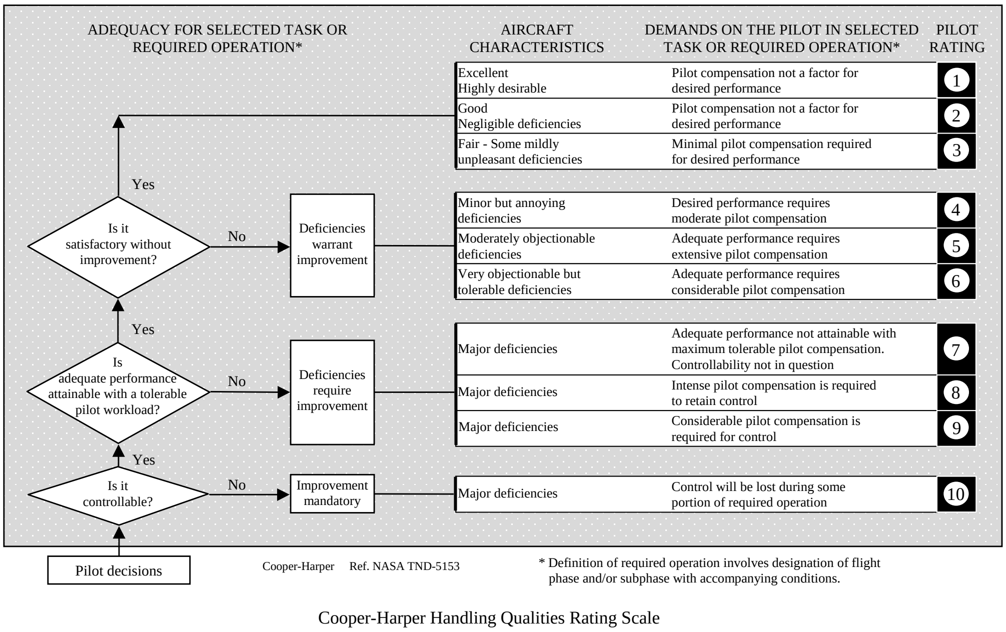


Figure 4.1: Cooper Harper Flying Qualities Rating Scale

the workload is either too high or too low, it can be detrimental to flight safety [55]. Workload is a difficult quantity to measure, since it is qualitative by nature, and different subjects will have different ideas about how to rate similar workload levels.

There is also a lack of specific workload information for flying qualities investigations. Since workload is implicit in the Cooper Harper rating scale, little other information concerning workload is presented for the majority of the flying qualities literature considered. In addition, workload tends to be difficult to measure and the workload scales can be complex in their use. However, workload is still a useful measure, especially as it can be used to distinguish between cases where the performance for a given task across a variety of pilots is constant, but the workload levels are significantly different [56].

The Use of Workload in this Study

The reasons for considering workload are stated below.

1. There is a requirement to examine the subjective pilot workload for given control laws;

2. To evaluate the perceived workload with different pilots for the same control law;
3. To evaluate the degree of pilot attention available to perform other cockpit tasks.

Workload scales should be able to characterise the difference in workload between different control laws, and also the effect of the autothrottle on the level of workload. It should also give an indication of the excess capacity within the pilot which may be used for other tasks which are not represented here, such as radio communications or navigational functions.

The Bedford workload scale was chosen for use for these evaluations due to its similarity to the Cooper Harper Rating, meaning that the pilots could quickly become accustomed to its format, and its ease of use. It is shown in figure 4.2. The NASA TLX scale [56, 54] and the Subjective Workload Assessment Technique (SWAT) scale [57] were also considered briefly and the NASA TLX scale used, but the results were not conclusive mainly due to the difficulty encountered in their use. The NASA TLX scale and its results are described within reference [58]

The Bedford Workload Scale

The Bedford scale was initially developed by Roscoe [59] and others at RAE Bedford and it is shown in figure 4.2. It is a 10 point rating scale, and has a similar format to the Cooper Harper scale. It is based on the concept of spare capacity, and was developed with the assistance of practising test pilots, and has been used by a large number of pilots in various flight trials and workload studies. It is simple to administer, and has been shown to correlate very accurately with more sophisticated workload scales [54].

In the same way as the Cooper Harper rating scale, the Bedford scale is designed for use with a specific piloting task. The Bedford rating is compiled by either completing up to three questions in a decision tree, or by an experienced pilot calling out a number.

The scale has been used in a variety of situations, from assessing aircraft flying qualities for a specific task to assessing the impact of technology, such as glass cockpits on pilot workload and effects due to the aircraft operating in specific conditions such as over the North Sea [59].

The Bedford scale is acceptable for a limited evaluation, but can be restrictive due to its simplicity. It does not distinguish between task-induced or operator-induced workload as some of the more complex scales such as NASA TLX do, and it has been found that it does not distinguish well between similar situations with different workload but constant performance.

4.1.3 The Pilot Induced Oscillation Rating Scale

The Pilot Induced Oscillation rating scale is generally used to give an indication of whether a particular aircraft is susceptible to Pilot Induced Oscillations for a particular task. It is shown in figure 4.3.

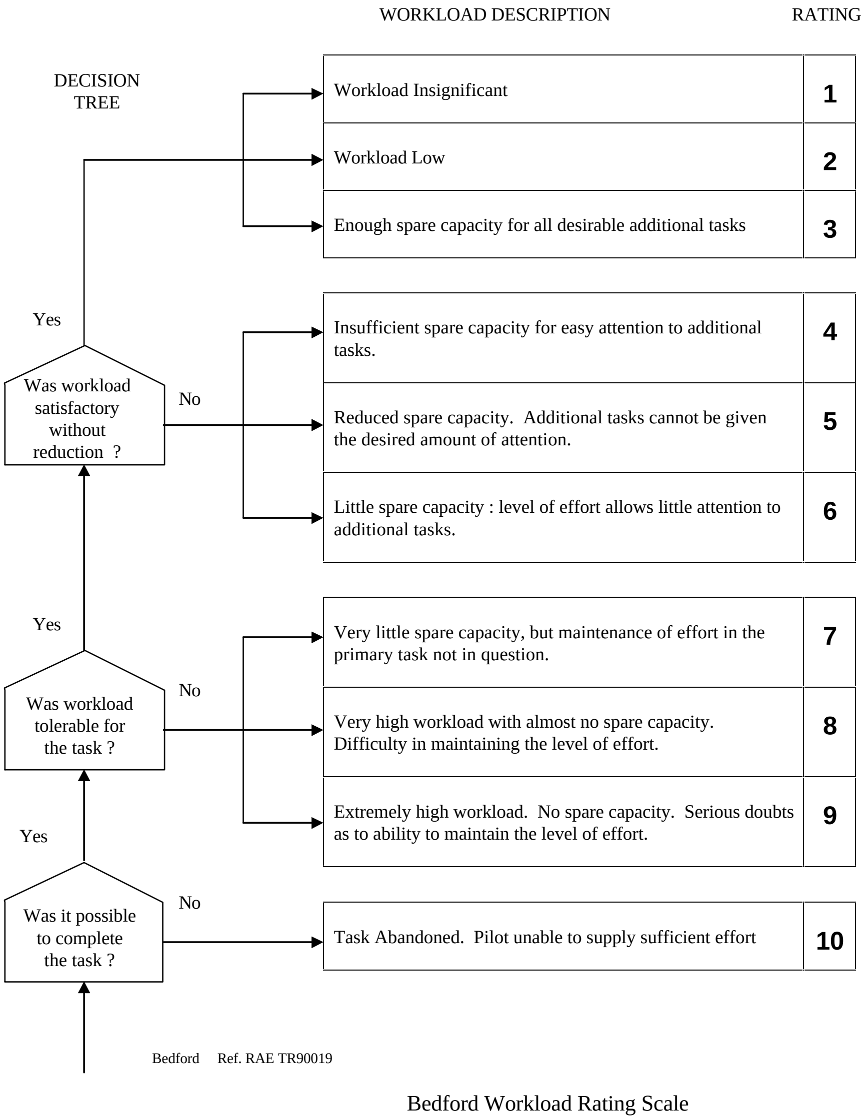


Figure 4.2: The Bedford Workload Scale

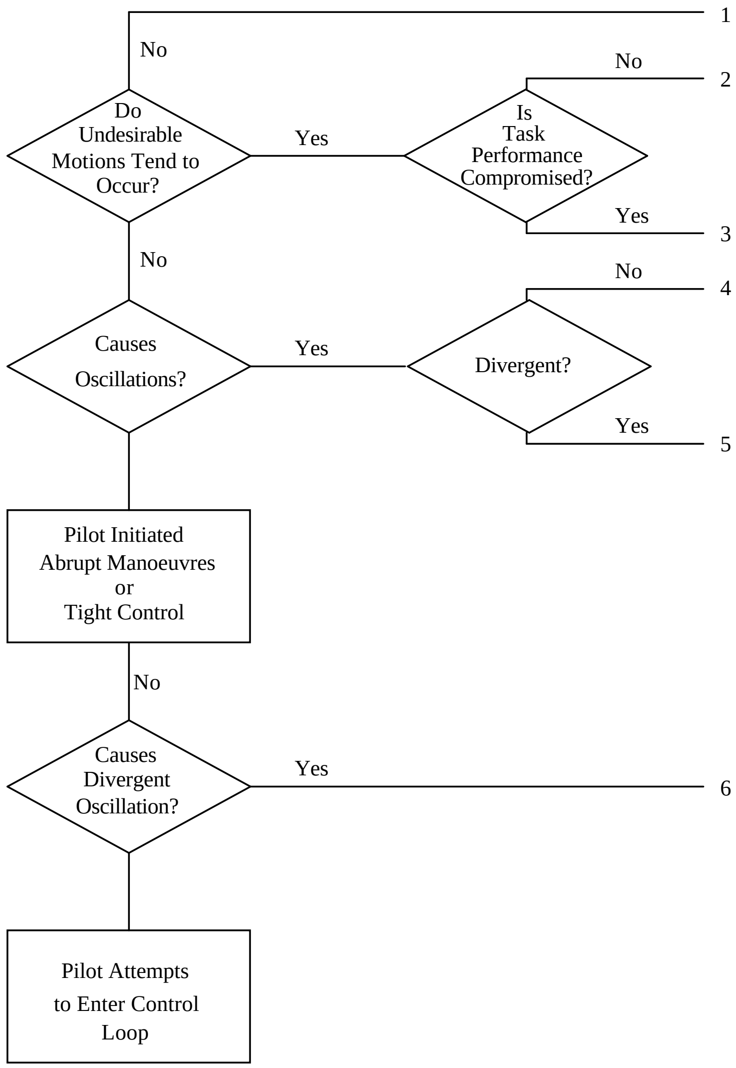


Figure 4.3: The Pilot Induced Oscillation Rating Scale

4.2 The Control Anticipation Parameter Criterion

The Control Anticipation Parameter was originally developed by Bihrle as a measure of the predictability of flight path control [60]. It is a measure of the relation between the pitch response and flight path response since the criterion assumes that if the two have the correct relationship, the pilot will be able to predict the flight path response from the pitch response observed or felt.

4.2.1 Original Derivation

The CAP value for a particular aircraft is defined by Bihrle [60] as the initial pitch acceleration divided by the steady state normal equation for a given input, nominally an elevator step. This is shown in equation 4.1.

$$CAP = \frac{\ddot{\theta}_{init}}{Nz_{SS}} \tag{4.1}$$

A low value of CAP represents low initial pitch acceleration for a given amount of steady state normal acceleration, and a high CAP value represents a high initial pitch acceleration for a given amount of steady state normal acceleration. After reduction, it can be shown that this is equivalent to equation 4.2. The derivation for this is given in reference [50].

$$CAP = \frac{\omega_{SP}^2}{n_\alpha} \tag{4.2}$$

where n_α is the lift curve slope and ω_{SP} is the short period mode natural frequency. Alternatively, the following expression may be used:

$$CAP = \frac{\omega_{SP}^2}{\frac{V}{g}\frac{1}{T_{\theta_2}}} \tag{4.3}$$

where V is the airspeed and g is the gravitational acceleration.

The CAP parameter may also be shown to be proportional to the aircraft manoeuvre margin for a classical aircraft [50]. These definitions are based on the dynamics of conventional aircraft since the process involved in developing equation 4.1 into equation 4.2 assumes that conventional aircraft dynamics are present.

The CAP boundaries for a Cat C task for a class III aircraft are shown in figure 4.4.

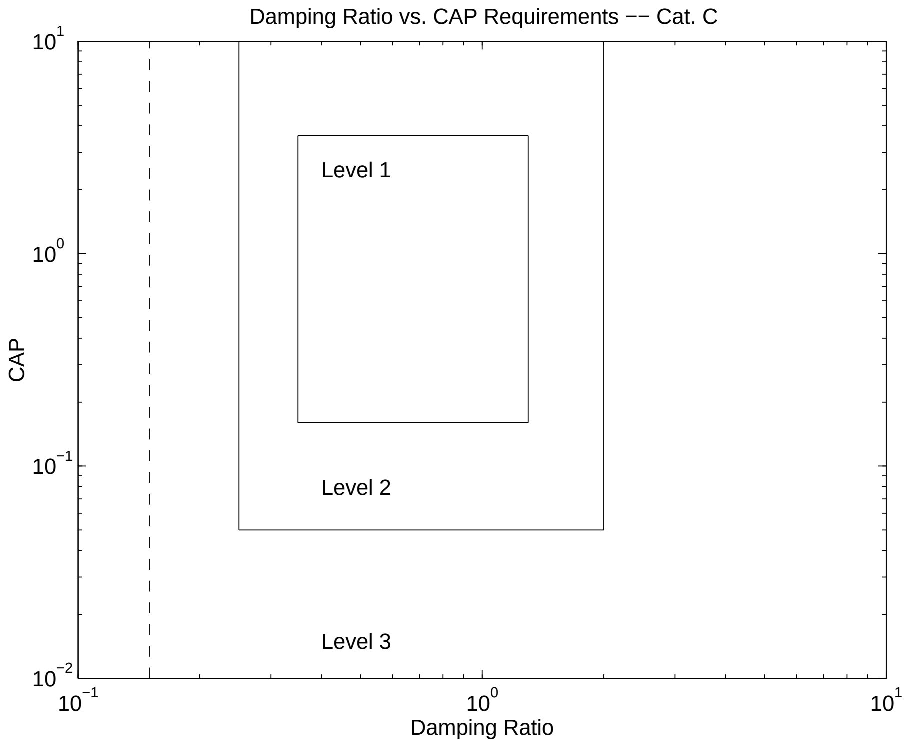


Figure 4.4: CAP Boundaries for Class III Cat C Flight Phase

4.2.2 The Steady Manoeuvring Force and Pitch Sensitivity Criterion (SMFPSC) Extension to the CAP Criterion

For a classical aircraft, the CAP criterion is calculated as a function of the short period mode natural frequency, the $1/T_{\theta_2}$ value and the airspeed. For non-conventional response types, the aircraft does not necessarily have a conventional short period mode and therefore the approximation used to derive the CAP equation (equation 4.2) may not be valid.

However, analysis of the theory behind the original CAP criterion shows that the ideas behind the criterion should be valid for alternate response types which approximate to a constant load factor for a step input, such as rate-like demand systems [50].

Therefore this criterion was developed to extend CAP for non-conventional response types. The effective CAP is derived by measuring the initial pitch acceleration and steady state normal acceleration for an elevator step input (with a constant throttle setting), and then evaluating the following formula:

$$|\frac{F_e}{Nz}|_{ss} \times |\frac{\ddot{\theta}}{F_e}|_{max} \tag{4.4}$$

which is equivalent to

$$\frac{\ddot{\theta}_{max}}{Nz_{ss}} \tag{4.5}$$

Note that this equation is identical to equation 4.1 which is the starting point for the CAP derivation. The resulting value is then plotted on the required CAP boundaries. This produces a number which is directly comparable with the CAP value for a given aircraft. It was used extensively at NLR, mainly for pitch rate demand systems [61, 62].

4.2.3 The Generic Control Anticipation Parameter Extension to the CAP Criterion

This section describes a further modification to the CAP parameter, described in detail in reference [50]. It extends the concepts behind the Steady Manoeuvring Force and Pitch Sensitivity Criterion (SMFPSC) to non-conventional response types.

Two main difficulties are experienced with the CAP and SMFPSC criteria. Firstly, the assumption that an aircraft will have a constant steady state normal acceleration response to a step demand is not always true. Secondly, the initial pitch acceleration may be influenced by the effects of actuator and other dynamics.

Reference [50] describes the two main modifications. Firstly, the maximum initial pitch acceleration in the first second of the response is used in place of the initial pitch acceleration as the maximum pitch acceleration is almost unaffected by the effects of actuator dynamics. Secondly, the peak normal acceleration is used in a modified form instead of the steady state value. This is because most response types with rate-like response types will have a peak normal acceleration.

Figure 4.5 shows the effect on the pitch acceleration response of adding a typical actuator to a classical aircraft. It can be seen that the effect of the actuator is to delay the build-up of pitch acceleration, but the differences between the initial pitch acceleration for the response without an actuator to the maximum pitch acceleration to the response with an actuator is small at less than 5 % for this particular case. The actuator is modelled using the transfer function shown in equation 4.6, i.e. as a second order lag with a natural frequency of 25 rad/s and a damping ratio of 0.7.

$$\frac{Output}{Input} = \frac{25^2}{s^2 + 2 \times 0.7 \times 25\ s + 25^2} \tag{4.6}$$

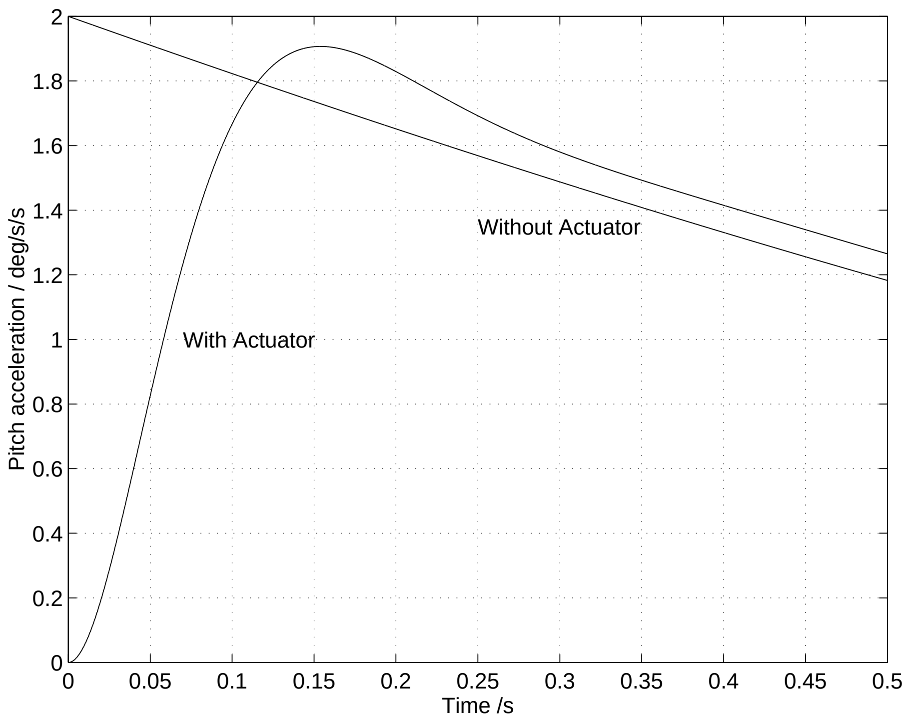


Figure 4.5: Effect on Pitch Acceleration Response to a Step Input of Adding an Actuator for a Classical Aircraft

For a second order response, as the normal acceleration response generally is, the relationship between the height of the first peak and the steady state value can be calculated for a second order system as long as the damping ratio of the second order system is less than unity [63]. Equation 4.7 is used to do this. The effect of adding an actuator into the system is negligible on the peak value and steady state value for a step input on a second order system, as shown in figure 4.6. Again, the actuator described in equation 4.6 is used.

$$\frac{y_{max}}{y_{ss}} = 1 + \exp\left(\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}\right) \tag{4.7}$$

Therefore, Generic CAP (GCAP) value may be derived as follows:

$$GCAP = \frac{\ddot{\theta_{init}}}{N_{Z_{ss}}} \tag{4.8}$$

For a classical unaugmented aircraft $\ddot{\theta}_{init}$ is more or less equal to $\ddot{\theta}_{max}$, and this may be seen in figure 4.5. The maximum pitch acceleration for the aircraft with no

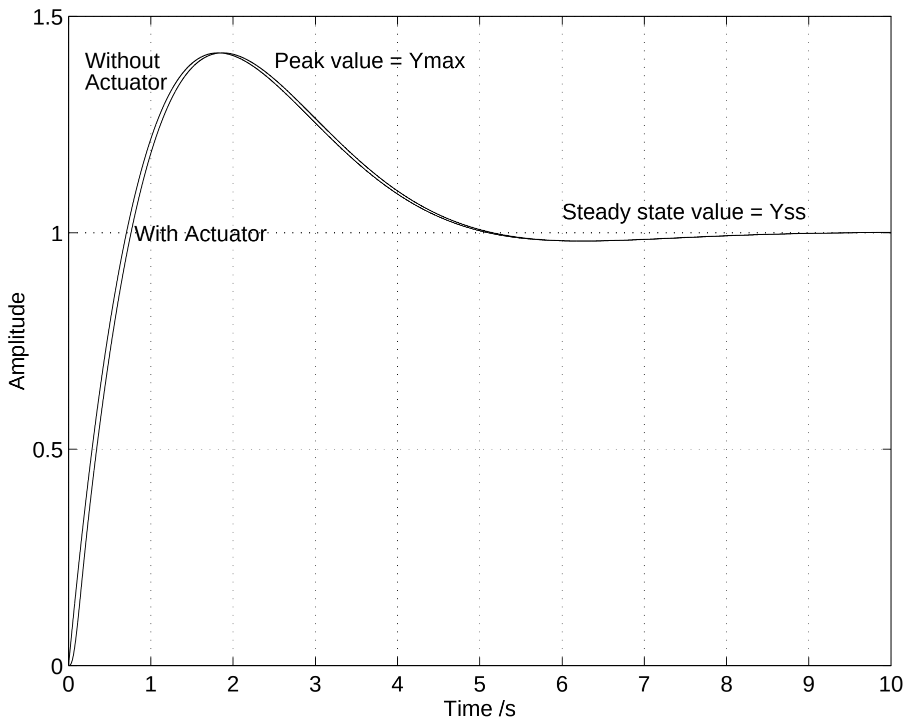


Figure 4.6: Relationship Between Peak and Steady State Value for a Second Order Response to a Step Input for a Classical Aircraft (Pitch Rate Response)

actuator occurs at a time of 0 seconds, whereas the maximum pitch acceleration for the aircraft with an actuator occurs at 0.15 seconds. The two 'maximum' values are within 5% of each other. Therefore considering the maximum pitch acceleration in the first second or so removes any variation in initial pitch acceleration due to the actuators, and the current work shows that this is an acceptable approximation [50]. Assuming that $\ddot{\theta}_{init} = \ddot{\theta}_{max}$,

$$GCAP = \frac{\ddot{\theta}_{max}}{N_{Z_{pk}}}.\frac{N_{Z_{pk}}}{N_{Z_{ss}}} \tag{4.9}$$

Therefore,

$$GCAP = \frac{\ddot{\theta}_{max}}{N_{Z_{pk}}}.\left(1 + \exp\left(\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}\right)\right) \tag{4.10}$$

Comparison between GCAP and the calculated CAP value show that the difference between the two figures is less than 10 % for 80 % of all reasonable classical aircraft responses considered and less than 5 % for 60 % of the responses. This seems like quite a close correlation, especially considering the approximations which have been made in the initial CAP analysis. Bihrle [60] states that the calculation for CAP using the above formula has an error of up to 10 % due to the assumptions made in order to simplify the equations.

This now implies that the CAP boundaries may now be used with alternative response types, since characteristics which are present in both the classical and non-classical aircraft responses, namely the initial pitch acceleration, the short term mode damping ratio and the first peak normal acceleration are being used for the computation of the CAP parameter. The fact that the long term response of the non-conventional law is different from the long term response of a classical aircraft should not pose a problem since CAP was initially derived as criterion for precise closed loop flight path control [60], and therefore the pilot will never let the aircraft respond to an input for more than a few seconds without modifying his input.

It is not known whether the pilot is sensitive to the peak or steady-state normal acceleration value. It is assumed here that the pilot is sensitive to the peak normal acceleration, and that the steady-state normal acceleration was used in the initial CAP derivation since it is mathematically easier to derive the CAP equation if it is used.

4.2.4 Advantages and Disadvantages of the CAP Based Criteria

The CAP criterion is generally accepted to be a good criterion for assessing aircraft, and forms the basis for the current US MIL-STD and UK Def Stan 00-970 flying qualities documents. It is simple to derive as it may be calculated directly and does not require or assume any form of pilot model.

CAP in its classical form is only applicable to aircraft with classical response characteristics. The GCAP criterion has been designed to overcome this difficulty though it is essentially untested. In addition, the CAP boundaries are very wide so selecting a suitable value of CAP for design purposes may be difficult. However, since CAP has been widely used as a design criterion, much information exists concerning suitable values for specified tasks and aircraft types.

4.2.5 The Application of the CAP Series of Criteria to the Present Work

A significant amount of use was made of Generic CAP as a design and analysis criterion for the work carried out here. Since it was developed as a part of this work, its usefulness will be assessed later in light of the results of the flying qualities evaluations.

4.3 The Low Order Equivalent Systems Tool

Low Order Equivalent Systems (LOES) is a low order mathematical model which matches an actual high order model responses into equivalent low order ones.

4.3.1 Original Description

Equivalent parameters have been widely used for comparison and correlation of the flying qualities of high order dynamics for a Conventional Take-Off and Landing (CTOL) and a Vertical Take-Off and Short Landing (V/STOL) aircraft. Where possible, the equivalent systems parameters are compared with suitably modified modal requirements, which gives reasonable prediction of flying qualities.

Typical classical low order equivalent systems use an equivalent system representation to match the actual pitch rate frequency response to a simplified frequency response over a defined frequency range, by varying the defining parameters on the simplified transfer functions. This therefore approximates the response of a high order aircraft by that of a second order system, coupled with a time delay, which partly represents the high order effects. Bounds are placed on the match between the high order system (HOS) response and the LOES approximation [64] in order to specify acceptable differences between the high order aircraft and low order match.

Typically, a high order aircraft is matched in one of two ways. Either a 'pitch-only' match is performed which matches the pitch rate transfer function, or a 'simultaneous' match is performed, which matches both the pitch rate and normal acceleration transfer functions simultaneously. The methods for performing these matches are widely documented and will not be reproduced here [65]. Although variations do exist, a typical equivalent pitch rate and equivalent normal acceleration transfer function in Laplace notation have been included here, see equations 4.11 and 4.12 respectively.

$$\frac{q_e}{\delta_e} = \frac{K_{q_e}(s + \frac{1}{T_{\theta_2}}_e)}{[s^2 + 2\zeta_{sp_e}\omega_{sp_e}s + \omega_{sp_e}^2]} \tag{4.11}$$

$$\frac{Nz_e}{\delta_e} = \frac{K_{nz_e}}{[s^2 + 2\zeta_{sp_e}\omega_{sp_e}s + \omega_{sp_e}^2]} \tag{4.12}$$

4.3.2 The Application of LOES to the Present Work

LOES is not used for analysis purposes within this thesis as it can sometimes be difficult to use and is not necessary for the design process. The flying qualities criteria used for this work are able to analyse response characteristics for both high order and low order aircraft and so there is no requirement to produce an equivalent low order aircraft. In addition, it was found to be difficult to use as the equivalent low order model is very sensitive to the frequency range over which the equivalent match is made.

However, it has been described here as it is included within the US Military standard on flying qualities document MIL-STD-1797A [66].

4.4 Gibson's Dropback Criterion

Dropback is a characteristic of the pitch attitude response for aircraft with rate-like responses. The criterion was developed by Gibson to improve the predictability of the aircraft longitudinal response following the removal of the control input.

4.4.1 Original Description

Dropback is a characteristic of the pitch attitude response and can be seen on figure 4.7. In a pitch rate command-attitude hold (RCAH) system, where the steady state pitch rate is constant and positive for a step input, dropback is where the pitch attitude 'drops back or decreases to a lower steady value after the input is removed, and 'overshoot' is where the pitch attitude continues to increase to a steady state value after the input is removed. Figure 4.7 shows dropback in the pitch attitude response.

Responses with different dropback levels can be seen on figure 4.8. Response A has positive dropback as the steady state pitch attitude is less than the pitch attitude when the input was removed. Response B has no dropback since the steady state pitch attitude is the same as the pitch attitude when the input was removed. Response C has negative dropback or overshoot since the steady state pitch attitude is greater than the pitch attitude value when the input was removed.

Pitch rate overshoot is also a component of the dropback criterion. Pitch rate overshoot is defined as the ratio of the peak pitch rate to the steady pitch rate in the pitch rate response, as shown in figure 4.6. It can be seen that response A on

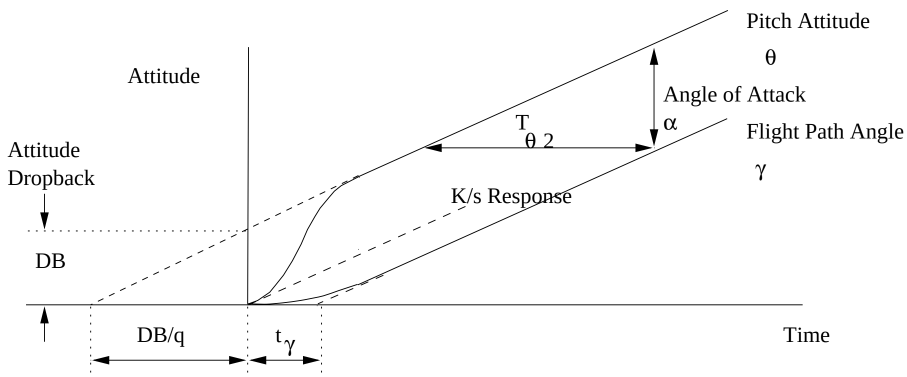


Figure 4.7: Pitch Attitude Dropback

figure 4.8 has a relatively high pitch rate overshoot, response B has a slightly smaller pitch rate overshoot, but still greater than unity and response C has a pitch rate overshoot less than unity.

The actual pitch attitude dropback value for a specified response is strictly an absolute angle and is shown as DB on figure 4.7. However, this dropback angle is effectively 'non-dimensionalised' by dividing by the steady state pitch rate. It is this parameter which is commonly referred to as the pitch attitude dropback or just dropback, and it has units of time. It is shown as DB/q on figure 4.7.

Dropback is strictly only relevant to pure pitch rate demand systems since there is a requirement for a constant steady state pitch rate to a step input, but it can be approximated for aircraft which have pitch-rate like characteristics in the short to medium term, which encompasses most of the rate-like response characteristics as well as the classical aircraft response.

When the pitch attitude dropback is zero, the pitch attitude response shows a pure K/s-like characteristic (see section 3.5) after the initial pitch rate transient is complete, i.e. it behaves like a pure integrator in pitch. Response B on figure 4.8 has zero dropback, i.e. it has K/s-like characteristics.

Pitch attitude dropback is also related to the flight path time delay, shown on figure 4.7 as t_γ. Flight path time delay is related to the pitch attitude dropback and T_{θ_2} values through equation 4.13. This is significant since for a given value of T_{θ_2}, increasing the dropback will reduce the flight path time delay.

$$T_{\theta_2} = \frac{DB}{q} + t_\gamma \tag{4.13}$$

The limits on pitch attitude dropback and pitch rate overshoot as proposed by Gibson for a pitch tracking task are shown on figure 4.9. Negative attitude dropback

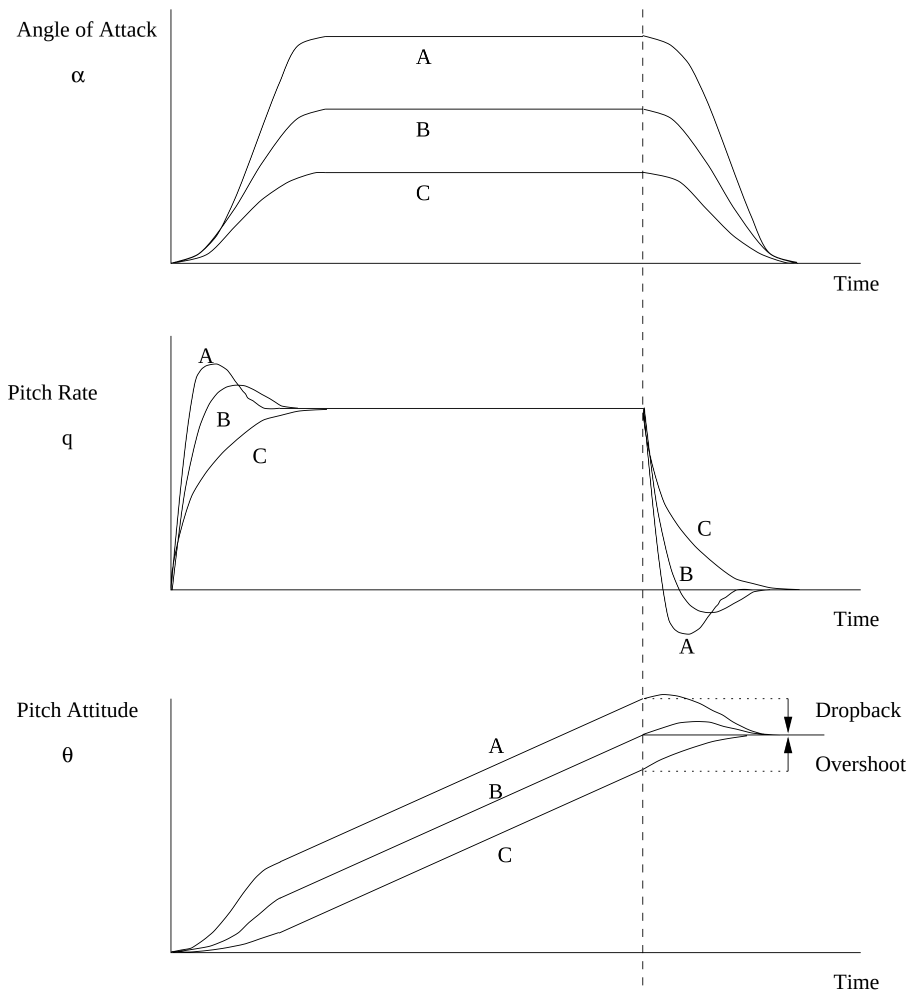


Figure 4.8: Varying Levels of Pitch Attitude Dropback

or overshoot is associated with a sluggish unpredictable response in both flight path control and pitch tracking [67]. Pitch attitude dropback (DB/q) in the range 0 to 0.25 seconds is excellent for fine tracking with comments like 'the nose follows the stick'. Pitch attitude dropback values of greater than 0.25 seconds lead to abrupt response and bobbling (oscillations) for precision tracking tasks. However, these limits are for class IV aircraft undergoing tracking tasks. Pitch attitude dropback has little effect on gross manoeuvring without a target, in-flight refuelling or landing, provided it is not negative. Gibson also states that a pitch attitude dropback value as high as 1 second may be acceptable for the approach and landing phase.

According to French [6], the dropback criterion may be improved slightly if upper dropback limit of 0.3 seconds is increased for class IV aircraft to permit lower values of $1/T_{\theta_2}$. French also states that the pitch rate overshoot must also be considered in relation to dropback since the two are heavily related. Pitch rate overshoot seems to qualify dropback behaviour, with a pitch rate overshoot of greater than 3 resulting in

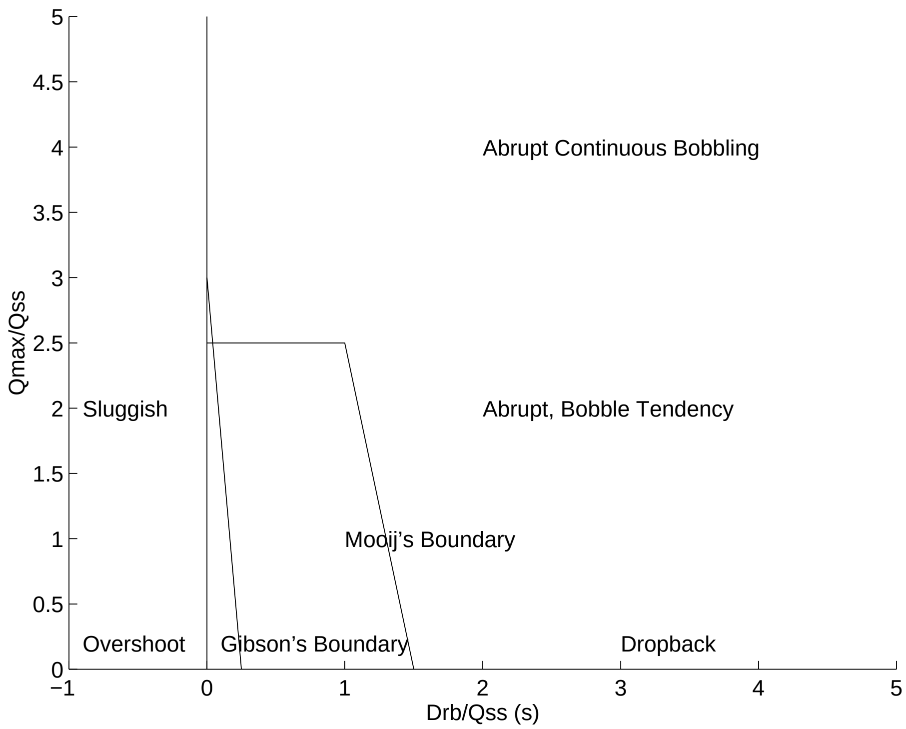


Figure 4.9: Gibson's Dropback Criterion Boundaries

unacceptable performance. Mooij [62] and Gibson [67] both show that the maximum permissible dropback reduces as the pitch rate overshoot increases.

According to Gibson [67], a small flight path time delay is excellent for flight refuelling control, but not essential for good gross manoeuvring and does not ensure predictable behaviour.

In summary [6], the dropback criterion is effective for assessing the acceptability of an aircraft's open loop pitch attitude response for precision tracking tasks. For aircraft with positive dropback, modifying the pitch attitude response to obtain zero dropback will not only provide a good (predictable) open loop response where the attitude remains fixed at an existing value when the input is removed, but also provides a better closed loop response at low frequencies. For approach and landing, dropback is an important consideration, not only for pitch attitude control, but also for its effect on the flight path delay.

4.4.2 The NLR Modifications made to the Dropback Criterion

The NLR Modified Gibson criterion defines overshoot and dropback limits for class III aircraft. This modification was made by Mooij at NLR [62]. The full order response is used when deriving the dropback value [68], and this criterion has tighter constraints than Gibson's original criterion [67].

The upper horizontal cut-off is established from space shuttle criterion and Mooij's experiments [68]. The criterion permits much greater dropback than Gibson (fighter combat manoeuvring) but allows less pitch rate overshoot, i.e. q_{max}/q_{ss}. The boundaries for Mooij's modified criterion can be seen in figure 4.9.

4.4.3 The Modifications made to the Dropback Criterion for this Work

The definition of the dropback criterion was modified for this work to render it suitable for response characteristics other than a 'perfect' pitch rate attitude hold response characteristic.

Figure 4.10 illustrates how this process was carried out for an aircraft without a steady state pitch rate. Considering the bottom of the three subplots (the pitch acceleration) shows that the pitch acceleration has 3 'minimum' values. The first is at the start (i.e. time zero), the second corresponds to the peak in pitch rate (at about 1.2 s) and the third is where the pitch acceleration has the minimum magnitude after the pitch rate peak. This occurs somewhere between 2 and 6 seconds, and also corresponds to the point where the magnitude of the pitch rate is changing the least. This is the point at which the pitch rate is assumed to be steady and it is termed the datum point. The pitch rate at that point is called the Effective Steady State Pitch Rate. The Actual Attitude Dropback may also be measured at this point, as shown in the figure, and is measured as an absolute angle.

Since the pitch rate is known at the datum point, a straight line may be drawn on the attitude plot (the top subplot) tangential to the pitch attitude response at the datum time and with a gradient equal to the pitch rate at the datum point (Effective Steady State Pitch Rate). The Actual Attitude Dropback is then also the distance between the point where this tangential line meets the 'y' axis and the origin. In this case it is approximately 1.75 degrees.

The steady pitch rate is a reference line drawn on the attitude plot, with a gradient equal to the pitch rate at the datum point, but this line passes through the origin.

$$\frac{Actual\ Attitude\ Dropback}{Effective\ Steady\ Pitch\ Rate} = \frac{1.7609}{1.1783} = 1.49s \tag{4.14}$$

The datum pitch rate is also used as the steady pitch rate in the ratio of maximum to effective steady state pitch rate calculation. The maximum pitch rate may be read directly from the pitch rate graph.

$$\frac{Maximum\ Pitch\ Rate}{Effective\ Steady\ Pitch\ Rate} = \frac{3.4659}{1.1783} = 2.94 \tag{4.15}$$

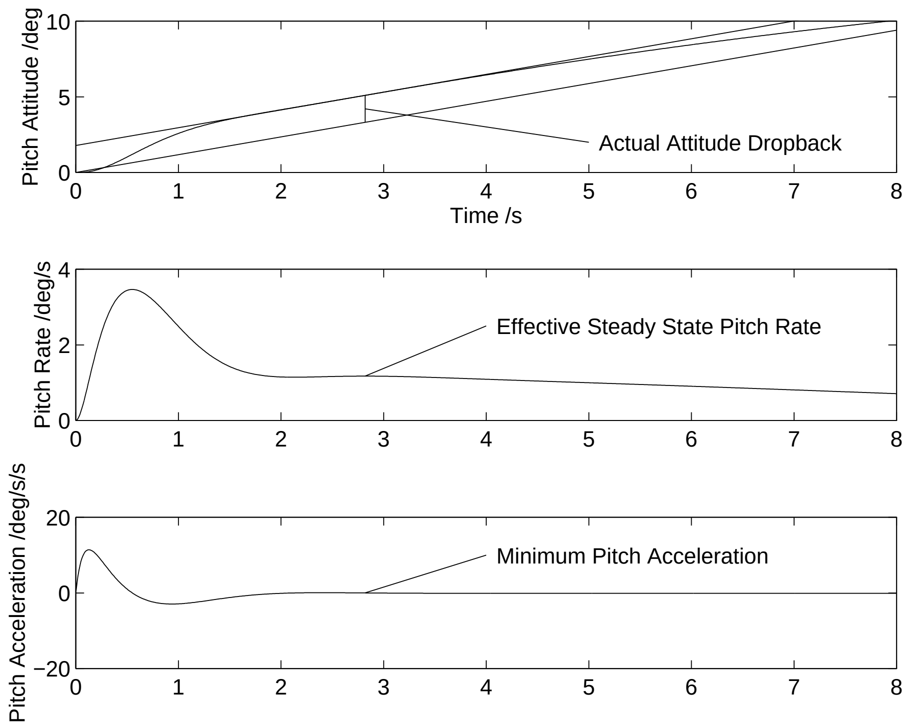


Figure 4.10: Pitch Response Characteristics for a Full Order Classical Response Type

4.4.4 Advantages and Disadvantages of the Dropback Criterion

The prime advantage of dropback is that it ensures that not only K/s properties are found in the short to medium term pitch attitude response, but that the flight path time delay value is specified. Excessive values of pitch attitude dropback or overshoot can lead to a response which is either too abrupt or sluggish for the pilot, and for precision attitude control tasks, the presence of excessive dropback or overshoot may make the task excessively difficult.

However, the pitch attitude dropback can be difficult to calculate for response characteristics other than the pitch rate response characteristic, and therefore care must be taken obtaining it. The method outlined above helps to specify how it should be obtained but experience with this method is low.

4.4.5 The Application of Dropback to the Present Work

Pitch attitude dropback is used as both a design and analysis criterion for the present work. In specifying the pitch attitude dropback, approximate K/s properties are kept and the flight path time delay is also specified. The pitch attitude dropback was calculated using the method described above, and Mooij's boundaries on figure 4.9 are used.

4.5 Sturmer's Pitch Sensitivity Criterion

Sturmer's pitch sensitivity criterion is a criterion which considers how the pitch rate to frequency response gain and phase characteristics change as the short term mode characteristics change [69]. It was conceived to place limits on the pilots' control forces.

4.5.1 Original Description

This application of this criterion requires a plot of open loop pitch rate gain (dB) against open loop phase (deg). The criterion then places bounds on this plot which correspond to flying qualities Levels. The boundaries are shown in figure 4.11, with the gain magnitude being equal to the value used for these evaluations.

Since little has been written concerning Sturmer's criterion, some investigative analysis was carried out by the author. The following comments refer to Sturmer's pitch sensitivity criterion and are based on trials carried out by the Author. The pitch rate transfer function shown in equation 4.16 was used.

$$\frac{q_e}{F_e} = \frac{K_q(s + \frac{1}{T_{\theta_2}})}{[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2]} \tag{4.16}$$

Since this criterion is designed to consider control forces, changing the control forces have a significant effect on the criteria. Increasing the pitch response per pound stick force (i.e. reducing the control forces) has the effect of moving a given plot on the boundaries vertically upwards, and vice-versa.

However, as the T_{θ_2} value changes there is little variation in the position of the pitch characteristic on the boundaries. There is little variation in pitch characteristic as the short period mode characteristics are varied slightly as long as the pitch

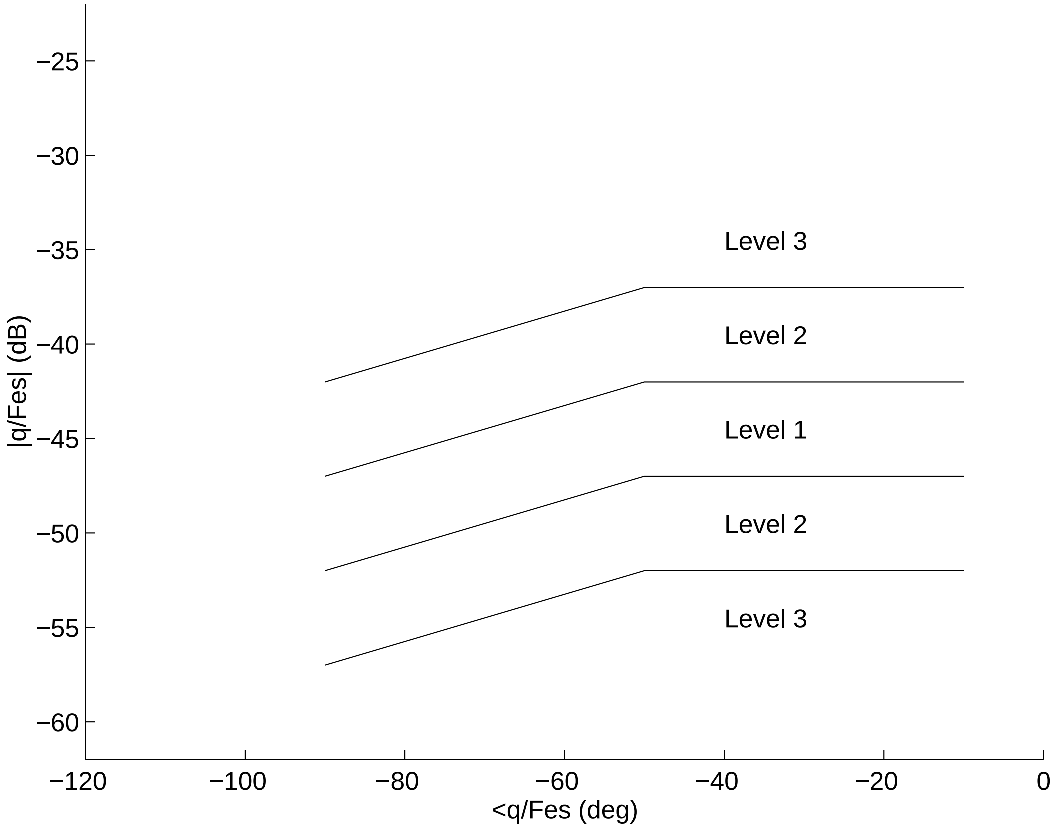


Figure 4.11: Sturmer's Pitch Sensitivity Criterion Boundaries

acceleration at 0.25 seconds is kept constant. Hence it may be said that the criterion is considering the pitch acceleration in the initial stages of the response, i.e. up to 0.25 seconds. Designing a number of aircraft with identical initial pitch accelerations does not give results which are quite so good. Sturmer also comments that the initial pitch acceleration should decrease for a decrease in short period mode natural frequency, which is the same effect.

Analysis of the boundaries show that Sturmer's criterion is concerned with the pitch attitude response when the pitch rate to elevator phase value is approximately -50 degrees which occurs at a frequency around the short period mode natural frequency. This is close to, but not the same as the frequency at which the maximum initial pitch acceleration ($\ddot{\theta}_{max}$) occurs.

Examination of the CAP criterion gives a useful insight. Recall the simple formula for calculating CAP:

$$CAP = \frac{\theta(\ddot{0})}{N_{Z_{ss}}} = \frac{\omega_n^2}{n_\alpha} \qquad (4.17)$$

Therefore,

$$CAP = \frac{\frac{\ddot{\theta(0)}}{F_e}}{\frac{N_{Z_{ss}}}{F_e}} \tag{4.18}$$

which leads to

$$\frac{CAP}{\frac{N_{Z_{ss}}}{F_e}} = \frac{\ddot{\theta(0)}}{F_e} \tag{4.19}$$

For a constant value of $\frac{N_{Z_{ss}}}{Fs}$ (or stick force per g), the value of $\frac{\ddot{\theta(0)}}{Fs}$ decreases as the short period mode natural frequency decreases [69]. Therefore Sturmer's criterion may be sensitive to stick force per g $(1/\frac{N_{Z_{ss}}}{F_e})$or a combination of initial pitch acceleration per unit stick force and stick force per g.

A further investigation was performed by the author which looked at the effect of varying the properties of the describing transfer function shown in equation 4.16. It was found that for values of ω_{sp}, ζ_{sp} and $1/T_{\theta_2}$ typical of those of a medium size civil transport aircraft, the pitch rate characteristics stayed within the Sturmer criterion boundaries for constant stick force per g.

With this in mind, it is interesting to note that different levels of stick force per 'g' which has traditionally been termed a steady state parameter can be distinguished by considering the pitch rate frequency characteristics around the short period natural frequency which is the frequency range under consideration on this criterion. It must also be remember that when considering the relationship between the maximum initial pitch acceleration and Sturmer's criterion, the maximum initial pitch acceleration will not be affected by pure time delays while Sturmer's criterion will be affected by the time delay since the time delay will affect the pitch attitude phase at a given frequency.

4.5.2 Advantages and Disadvantages of Sturmer's Criterion

Sturmer's criterion has had little visible exposure to the flying qualities world, yet from the little evidence that is present it would seem that it could be a useful criterion for determining control forces. It is certainly sensitive to the stick force per 'g' for a particular aircraft.

4.5.3 The Application of Sturmer's Pitch Sensitivity Criterion to the Present Work

This criterion has been used in this work to analyse the control forces in an attempt to provide additional data.

4.6 Gibson's Attitude Frequency Response Boundaries

Gibson proposed boundaries for the pitch attitude frequency response characteristic. These are of the form of boundaries placed on a Nichols chart of the open loop pitch attitude frequency response. The boundaries were an attempt to specify the pitch attitude frequency response requirements for either up-and-away flight or the approach flight phase.

4.6.1 Original Description

These boundaries were proposed from the aircraft receiving the best flying qualities ratings from the following two sets of experimental data [70, 71]. Separate boundaries were proposed for the up and away (figure 4.12) and the landing phase tasks (figure 4.13).

For the landing phase, the boundaries were found to be best correlated by plotting them on a relative amplitude scale, with the 0dB point co-incident with the 120 degree phase lag for the landing approach phase, and at the 0.3 Hz frequency point for the up and away phase [72]. However, it must be remembered that these boundaries are for fighter aircraft. These results confirmed the usefulness of a K/s attitude response (i.e. a pitch rate demand system) at low frequencies, and placed boundaries on the higher frequency response.

These boundaries were redefined further in later years, and have been widely used for pitch tracking design [72]. One application has been the McDonnell Douglas C-17 [73]. The up-and-away Gibson boundaries were used with the C-17 in the air-to-air refuelling task. The initial C-17 control laws were found to be PIO prone in this flight phase, and therefore improvements were made based on Gibson's boundaries. This resulted in the aircraft having much improved flying qualities for this particular task.

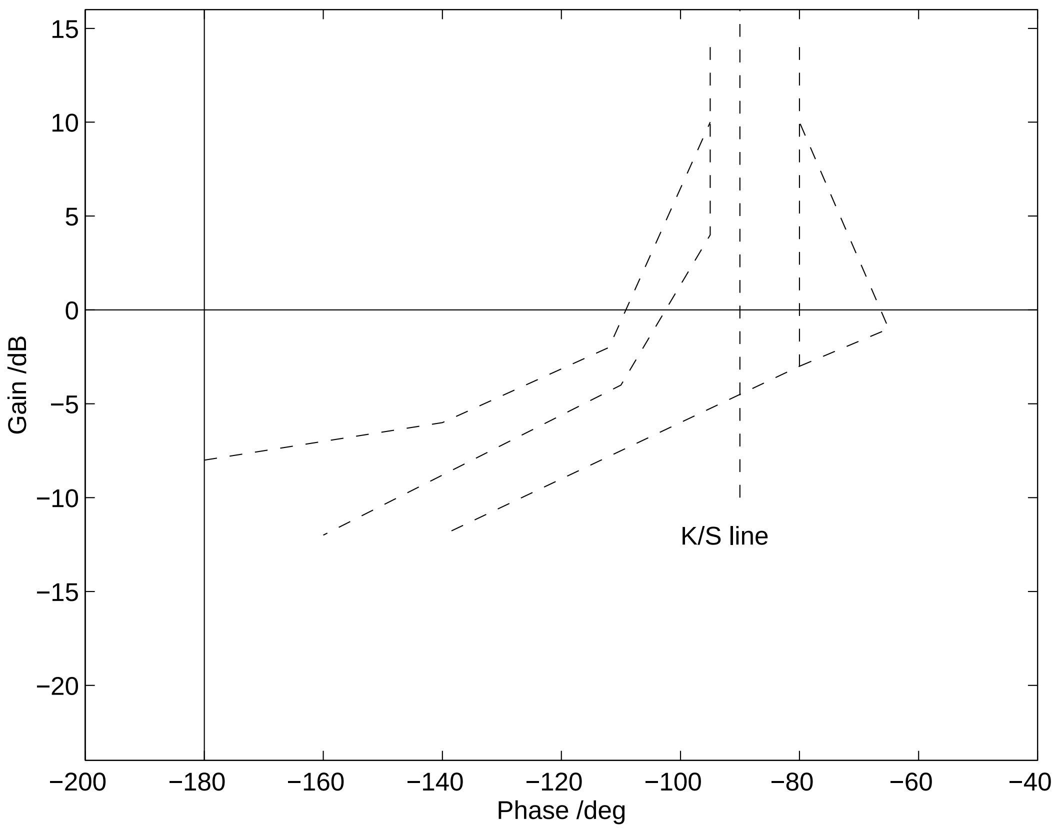


Figure 4.12: Gibson's Up-And-Away Frequency Response Boundaries

4.6.2 The Advantages and Disadvantages of Gibson's Frequency Boundaries

These boundaries are simple to apply and seem to work reasonably well [73]. However, little information could be found concerning their application.

4.6.3 The Application of Gibson's Frequency Boundaries to the Present Work

As with Sturmer's pitch sensitivity criterion, this criterion has been used in this work to analyse the pitch attitude frequency response characteristics and in an attempt to provide additional data.

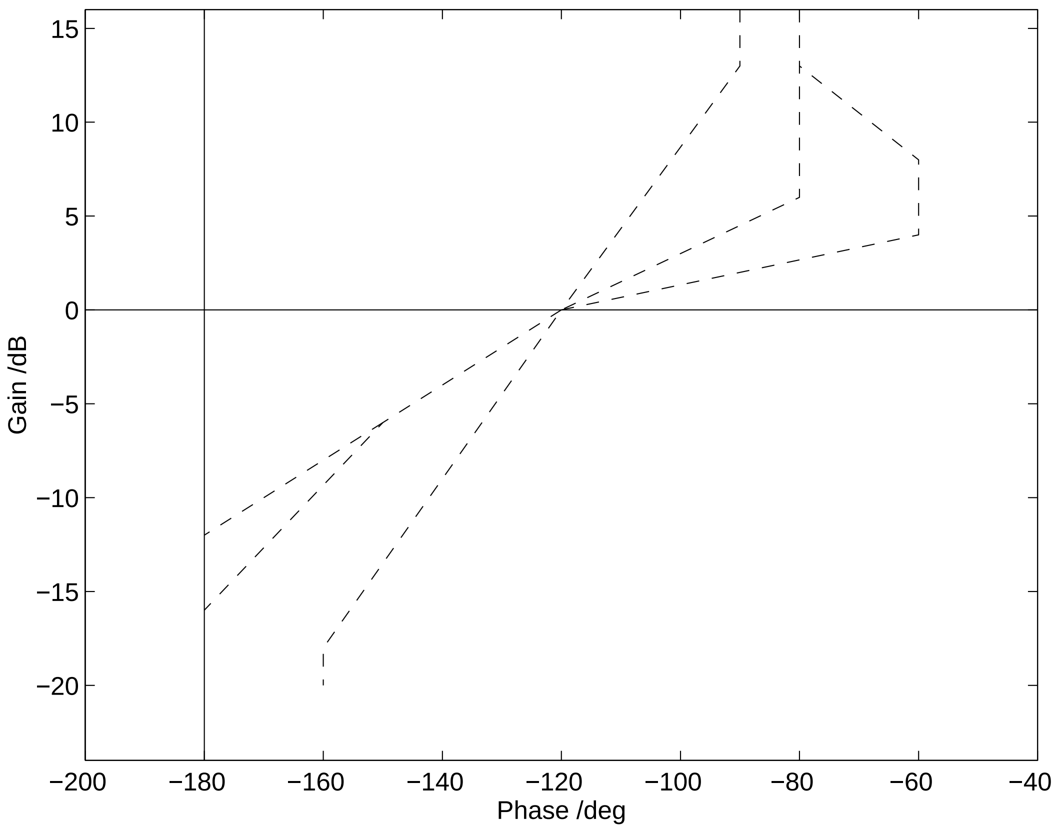


Figure 4.13: Gibson's Landing Frequency Response Boundaries

4.7 The Bandwidth Criterion

This criterion was developed as a simple method to assess the suitability of the open loop pitch attitude to stick force transfer function [74]. The criterion attempts to define a range of pitch control frequencies over which the aircraft has good response characteristics, and it is a task orientated criterion.

4.7.1 Original Description

The bandwidth criterion is made up of two requirements; firstly a time delay-like requirement (called phase delay) to account for time delays and higher order dynamics and secondly the bandwidth of the aircraft transfer function. The bandwidth and phase delay are then used to determine the flying qualities level of the aircraft.

The bandwidth is defined from a bode plot of the augmented aircraft. It is the lower of the two frequencies where the gain margin is 6 dB and the phase margin is 45 degrees. If the lower of the two frequencies is the frequency where the phase margin is 45 degrees, the aircraft is said to be phase margin limited. Otherwise the aircraft is gain margin limited. These definitions are shown on figure 4.14. The concept of Bandwidth is applicable to the flight path angle as well as the pitch attitude frequency characteristics, and the application of the criterion requires both bandwidths to be calculated.

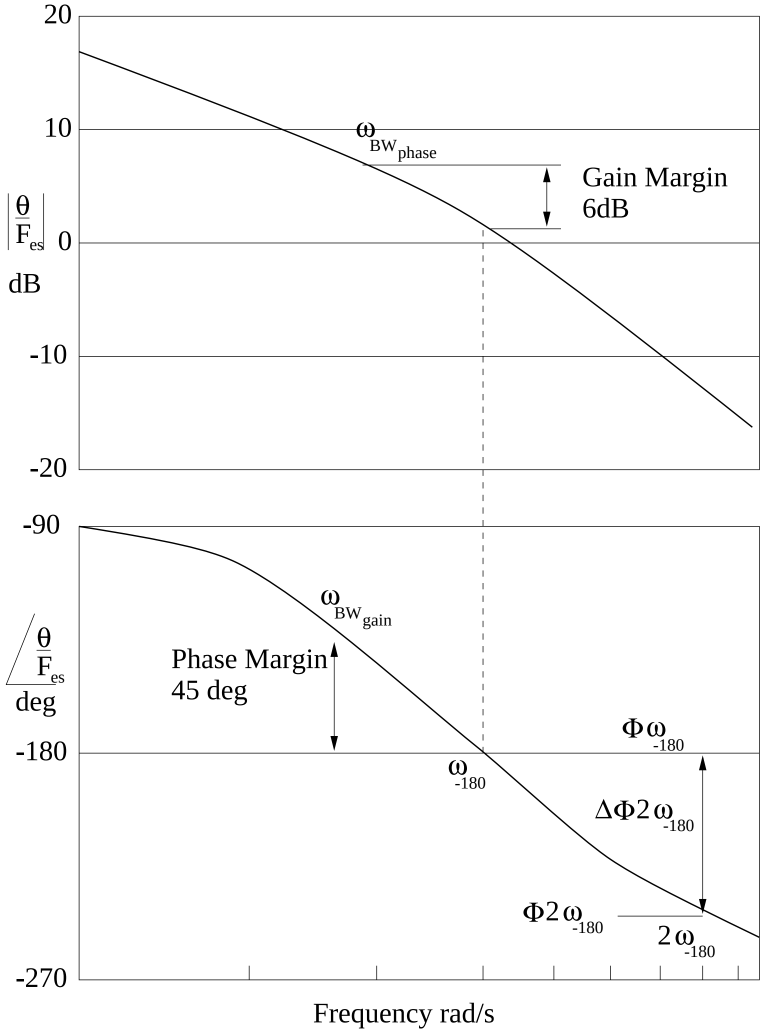


Figure 4.14: Definitions used in the Bandwidth Criterion (from reference [1])

The gain margin of 6 dB is derived from experience which shows that a smaller gain margin may give a PIO prone aircraft. A 6 dB gain margin allows the pilot to double his gain before instability is reached. The phase margin of 45 degrees requires full pilot attention but less than maximum pilot effort [74]. Bandwidth therefore describes the ability of a pilot to follow a range of input frequencies with the bandwidth being related to the highest frequency that the pilot can follow.

The phase delay parameter is calculated from the slope of the phase curve above the crossover frequency. The crossover frequency is the frequency where the phase first passes through -180 degrees. The phase delay, expressed as τ_P may be calculated using the formula in equation 4.20. The derivation for this is given in French's thesis [6]. This is also proportional to Gibson's phase rate parameter, discussed later.

$$\tau_P = -\frac{\Phi 2\omega_{-180} + 180}{57.3 \times 2\omega_{-180}} s \tag{4.20}$$

This is derived as follows. Firstly,

$$\Delta\Phi = \tau_P \Delta\omega \tag{4.21}$$

Therefore,

$$\tau_P = -\frac{\Phi 2\omega_{-180} - \Phi\omega_{-180}}{2\omega_{-180} - \omega_{-180}} \tag{4.22}$$

But $-\Phi\omega_{-180}$ is -180 degrees by definition, which is -180/57.3 rad. Therefore,

$$\tau_P = -\frac{\Phi 2\omega_{-180} + 180/57.3}{\omega_{-180}} \tag{4.23}$$

which leads to equation 4.20 when the phase angles are given in degrees.

The bandwidth criterion is task and class orientated since the frequency that a pilot will need to control the aircraft for particular task is dependent on the task itself as well as the aircraft class, and therefore the appropriate bandwidth limits must be chosen when applying the criterion. Bandwidth is an application of the crossover model, the concept of which is that a human can be treated as an element of a closed loop system for compensatory tracking tasks.

When the bandwidth and phase rate have been determined, they may be plotted on the appropriate boundaries to determine whether a particular aircraft complies with the criterion. The bandwidth boundaries for a Class III (transport) aircraft in Cat C flight are shown in figures 4.15 and 4.16.

An aircraft's pitch attitude bandwidth or flight path angle bandwidth is very dependent on its short period natural frequency (for a conventional aircraft), or the short term mode natural frequency (for a non-conventional aircraft) and therefore any limit implied on the short term mode frequency would imply a limit on the bandwidth of that particular aircraft.

Efforts to develop the bandwidth criterion showed that the pilot is sensitive to the shape of the pitch attitude phase curve at frequencies beyond the bandwidth frequency. This is defined by the phase delay parameter. Physically, phase delay is a measure of how a pilot behaves as he increases his crossover frequency or tries to control the aircraft beyond the bandwidth frequency. Large values of phase delay indicate that there is a small frequency difference between normal tracking at 45 degrees phase margin and instability. A PIO-prone aircraft is frequently has a high phase delay due to a high time delay or unsuitable dynamics around the crossover point.

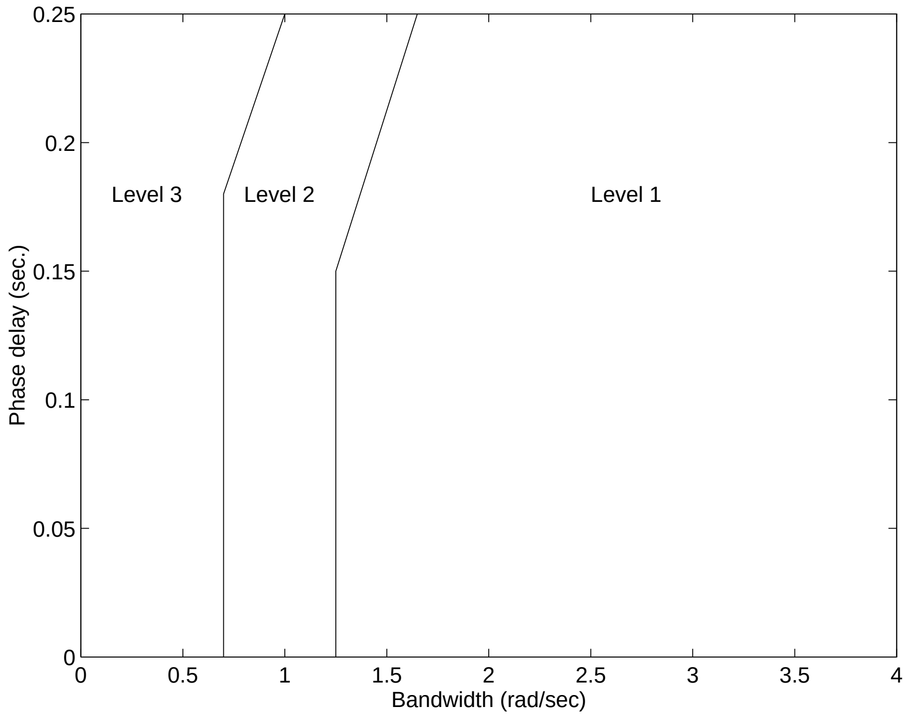


Figure 4.15: Phase Delay versus Pitch Attitude Bandwidth Boundaries

4.7.2 Advantages and Disadvantages of the Bandwidth Criterion

Phase delay assumes that the critical part of the phase curve is for frequencies below -180 degrees. In a classical unaugmented aircraft, the pitch attitude phase response does not decrease below -180 degrees; therefore any phase angle more negative than this is due to phase delay. It is not known if the initial assumption, i.e. the critical part of the phase curve is at frequencies above -180 degrees is true.

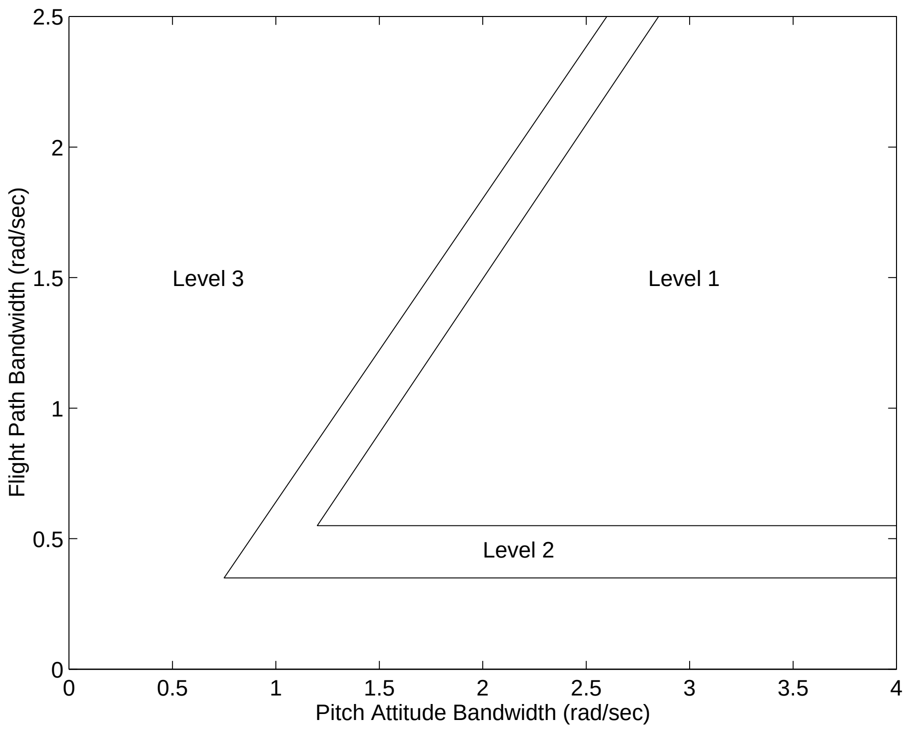


Figure 4.16: Flight Path Bandwidth versus Pitch Attitude Bandwidth Boundaries

French [6] questions the use of bandwidth, and suggests that crossover frequency might be more appropriate to use compared with bandwidth since the crossover frequency has a direct bearing on aircraft stability.

Bandwidth is generally accepted to be applicable to tasks which require closed loop compensatory tracking. Such tasks involve small amplitude attitude changes. Inflight and ground simulation has shown that the bandwidth requirement decreases as the amplitude of the manoeuvre increases. Therefore the mission orientated flying qualities must account for this by specifying limits which depend on the task being carried out. For very large amplitude manoeuvres, the pilot operates in an open loop manner [1].

It was found by Weingarten and Chalk [75] that closed loop pitch attitude bandwidth requirements for civil transport aircraft are less than for fighter aircraft with a value of 1.5 rad/s being required for civil aircraft in the approach task. It was found that the evaluation pilots applied a less rigorous standard to the approaches because the aircraft evaluated were defined as large and heavy aircraft and the pilots therefore accepted increased time delays. However, according to Berthe, Chalk and Sarrafian [76], bandwidth does not provide an adequate flying qualities prediction when based on pitch attitude alone.

Hoh [74] states that flight path bandwidth is a good indicator of flying qualities in the flare. Poor flight path characteristics due to increased flight path time delay can be improved to some extent by increasing the pitch rate overshoot and reducing the attitude dropback. The use of Direct Lift Control (DLC) may increase the flight path bandwidth, but it can be overdone resulting in too much flight path response and complaints from pilots. Therefore an upper flight path bandwidth boundary should be used. The upper boundary appears to be motion-induced, evident from in-flight simulators and is not apparent from fixed base simulators [4].

Field [4] also found that there may be an upper limit on bandwidth as he found that the aircraft became too abrupt when their bandwidth was increased above a certain value. However, this upper limit may be based on the sensitivity of a particular aircraft, i.e. the level of the control forces. He found that as the bandwidth reduces to the lowest permissible value, the upper and lower sensitivity limits progressively separate, until the greatest available pitch sensitivity range is obtained at the lowest permissible bandwidth frequency. However, according to Hoh, the upper bandwidth limit tends to be defined by stability boundaries [74].

4.7.3 The Application of the Bandwidth Criterion to the Present Work

The Bandwidth criterion is used to analyse the control law response characteristics for the present work, though it is not explicitally used as a design criterion since it is important to ensure that the bandwidth is suitable, but there are other criteria which can specify the response characteristics more precisely (such as CAP and Gibson's pitch attitude dropback).

4.8 Gibson's Phase Rate Criterion

This criterion was defined to help prevent the PIO problem in aircraft with high order systems [77]. It is similar to the phase delay component of the bandwidth criterion.

4.8.1 Original Description

The phase rate criterion uses the pitch attitude phase crossover frequency and a custom defined phase rate parameter to characterise the open loop pitch attitude frequency response [77]. Phase rate is a measure of the slope of the phase curve for frequencies approaching and just past the phase crossover frequency, i.e. the critical region. Accordingly, the phase rate criterion correlation parameters are considered more suitable than those utilised by the bandwidth criterion.

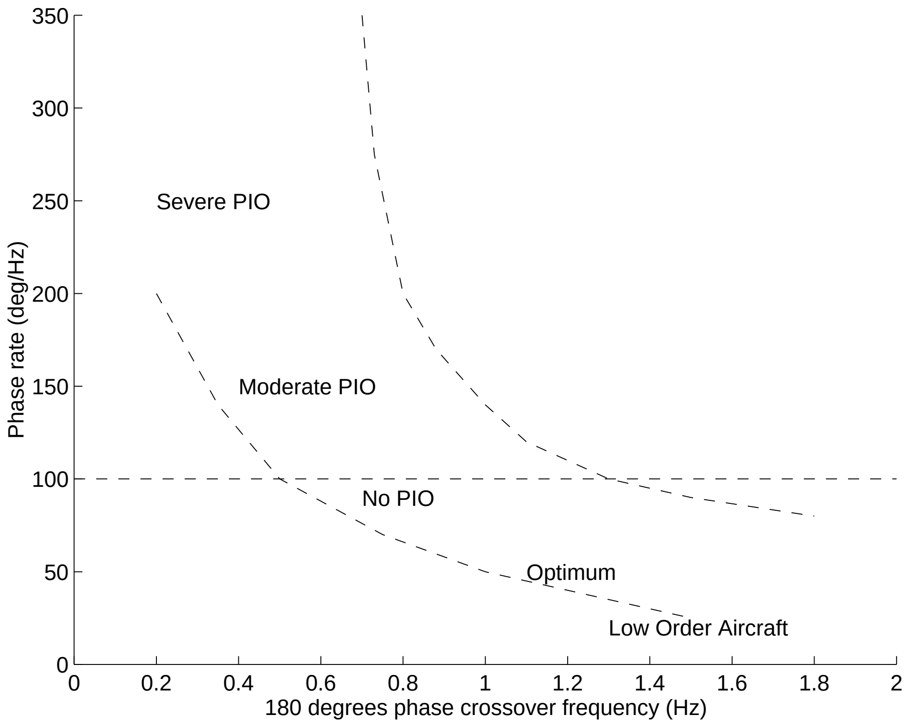


Figure 4.17: Boundaries for Gibson's Phase Rate Criterion

Phase rate has been defined using equation 4.24, which can be used to show a connection between phase rate and phase delay is similar to the phase delay equation from the bandwidth criterion 4.20. The terms used in equation 4.24 are defined on figure 4.14.

$$Phase\ Rate = \frac{\Phi 2\omega_{-180} - \Phi\omega_{-180}}{2\omega_{-180} - \omega_{-180}}\ deg/Hz \tag{4.24}$$

Therefore the phase rate parameter may be calculated from the phase delay parameter by substituting equation 4.20 into equation 4.24, which leads to equation 4.25.

$$\tau_p = \frac{Phase\ Rate}{4\pi \times 57.3} \tag{4.25}$$

Gibson found a good correlation between PIO data and the rate at which the pitch attitude phase lag increases with frequency in the crossover region (i.e. phase rate), which is the frequency at which the PIOs tend to occur. A low order response tends to attenuate quickly to a high frequency crossover with a low phase rate while a high order response tends to attenuate slowly towards a low frequency crossover with a high phase rate. Gibson also found the criterion was applicable to the approach and landing or pitch tracking tasks.

In applying the phase rate criterion, the values of the phase rate and phase crossover frequency are computed, and compared to the known limits on figure 4.17. A phase rate of less than 100 deg/Hz is required to ensure PIO is avoided.

Although the phase rate criterion is an open loop criterion, its purpose is to confirm that acceptable closed-loop operations can be achieved without any likelihood of PIOs. To do this, the criterion examines the characteristics of the open loop pitch attitude frequency response and compares them against that of a low order aircraft, which rarely exhibit PIO tendencies. The limits imposed by the criterion merely try to ensure that suitable margins exist for the pilot to introduce his own gain and phase compensation without threatening stability. Accordingly, the approach followed is very similar to the bandwidth criterion. PIOs resulting from stick pumping can be due to insufficient bandwidth and stability margins. If the phase crossover frequency is within the region of piloted crossover and the phase rate is high, increasing pilot gain or introducing additional phase lag will result in a rapid convergence of ω_{0dB} and the crossover frequency, and hence closed loop instability. In the landing phase, which has been shown to be a high gain demanding task, the combination of low phase crossover frequency (i.e. too low bandwidth) and high phase rate will result in PIO tendencies.

In relation to stability considerations, the slope of the phase curve is most critical for frequencies approaching and just after the phase crossover frequency, since this will determine the frequency at which the phase and gain margin decrease with increasing gain or phase lag. The PIO region defined by Gibson will determine the PIO frequency (which will be greater than ω_{-180}), since it is at this frequency that the response first becomes unstable. Accordingly the use of phase crossover frequency and phase rate as correlation parameters give the criterion good credibility as these parameters relate directly to the pilot-vehicle closed loop stability for a given task.

In Blagg's analysis of handling qualities criteria [51], he describes phase rate as providing excellent design guidance and should be used, subject to validation.

4.8.2 Advantages and Disadvantages of Gibson's Phase Rate Criterion

Experience in using this criterion has shown that it is easy to apply, and is very good at discerning aircraft with excessive phase delay and PIO tendencies from aircraft which are less PIO prone. However, it is only sensitive to time delay and does not generally discriminate between good and poor aircraft which have different short term dynamics but similar levels of phase rate.

4.8.3 The Application of Gibson's Phase Rate Criterion to the Present Work

This criterion has been used in conjunction with the phase delay requirement within the bandwidth criterion to check that the phase delay or phase rate for a particular aircraft is not excessive, i.e. is likely to give PIO problems.

4.9 The Neal-Smith Criterion

The Neal-Smith criterion was initially developed for class IV (fighter) aircraft [78]. Modification were subsequently made by Mooij to make it applicable for Class III (transport) aircraft [62].

4.9.1 Original Description

The Neal-Smith criterion is essentially concerned with a pilot modelling task. It works by calculating the required pilot gain and phase to place the aircraft / pilot pitch attitude transfer function phase angle at -90 degrees at the Neal-Smith bandwidth frequency. This frequency is specified for a particular aircraft type and task and must not be confused with the transfer function bandwidth as defined within the bandwidth criterion. This is done through the use of a pilot model transfer function, shown in Laplace notation in equation 4.26.

$$P_{PC}(s) = K_P e^{-\tau s} \frac{(1 + \tau_{p1} s)}{(1 + \tau_{p2} s)} \tag{4.26}$$

The parameters K_P, τ_{p1} and τ_{p2} can be determined from the required pilot lead / lag and gain compensation requirements. The amount of phase compensation may then be determined and correlated with the pilot opinion rating. The pilot model / aircraft interaction is shown in figure 4.18.

The Neal-Smith criterion is primarily based around the assumption that a pilot's comments concerning his compensation are closely related to whether he has to generate phase lead or lag. Since the phase characteristics are important in the vicinity of the Neal-Smith bandwidth frequency, it seems logical to describe the pilot's phase compensation in terms of the phase angle calculated from the τ_{p1} and τ_{p2} values given in equation 4.26. The phase angle is positive for lead compensation and negative for lag compensation. Hence, when the pilot states that he has to

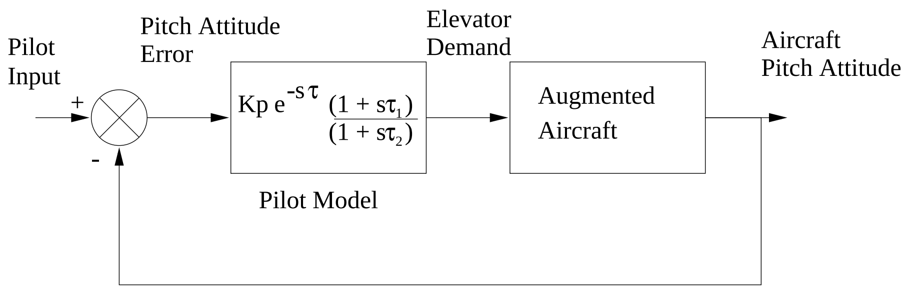


Figure 4.18: The Neal-Smith Pilot / Aircraft Interaction for Pitch Tracking Task

overdrive the aircraft, he is applying lead and when he states that he has to fly it smoothly, the compensation will be lag to smooth out the response of the 'abrupt' aircraft.

The Level 1 Neal-Smith boundaries for the approach flight condition are shown on figure 4.19. The original boundaries were devised by Neal and Smith [78], and the revised boundaries were developed by Smith [70], using a different bandwidth frequency (3 rad/s in place of the original 3.5 rad/s). A typical pilot time delay used is 0.2 seconds.

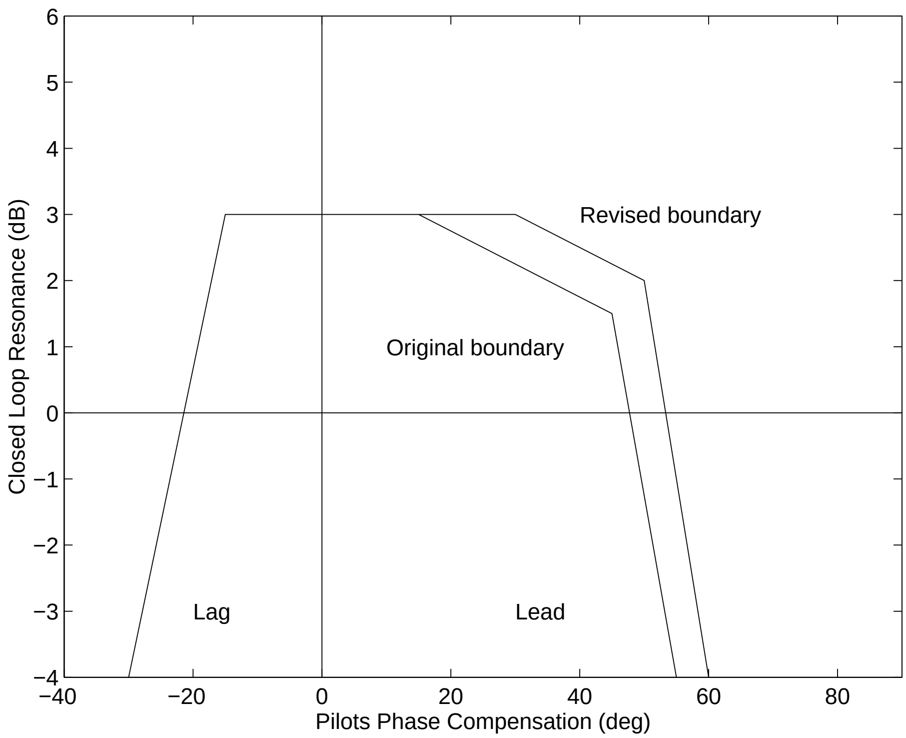


Figure 4.19: Neal-Smith Boundaries for Level 1 flight, Category C, Class III

4.9.2 The Modified Neal-Smith Criterion

The modified Neal-Smith criterion for transport aircraft is defined by Mooij [62] for the final approach and landing phases of the mission of a transport aircraft. Acceptable dynamic characteristics of the pilot/aircraft closed loop system for pitch-attitude control are quantified.

The modification was developed in order to account for deficiencies in the Neal-Smith criterion when applied to transport aircraft, following experiences using the NLR ground based simulator and the USAF TIFS, which involved flying a medium weight transport aircraft on an ILS approach to touchdown. The modified boundaries are plotted on figure 4.20.

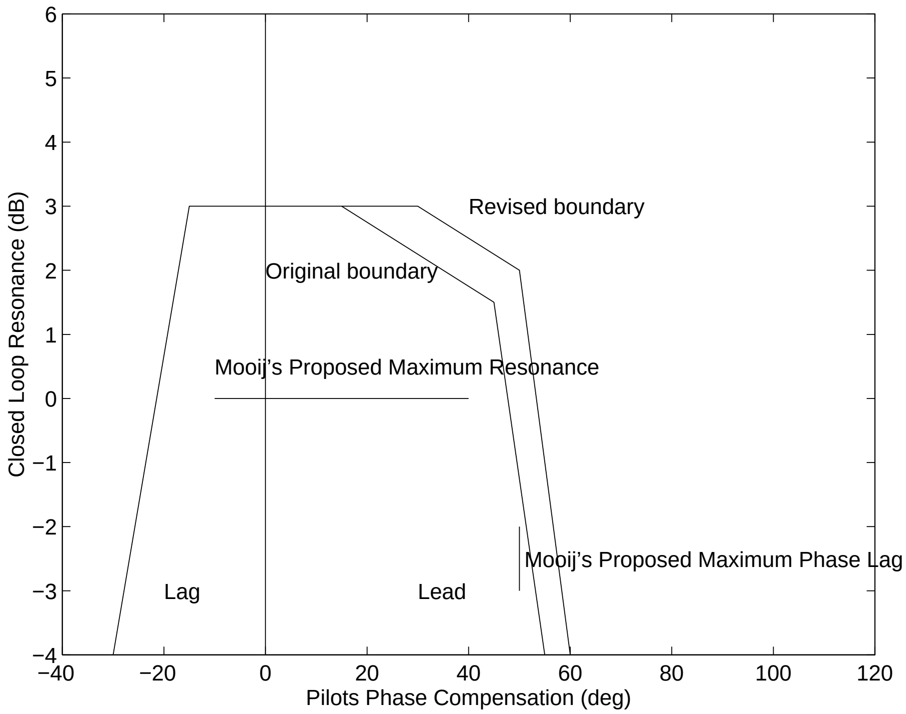


Figure 4.20: Mooij's Modified Neal-Smith Boundaries for Level 1 flight, Category C, Class III

The basic principles behind this modified criterion are the same as the original Neal-Smith criterion, where the pilot's perception of the aircraft handling qualities is closely related to whether he has to provide phase lead or phase lag compensation. Phase characteristics are most important in the region around the bandwidth frequency, and this causes the majority of the problems with the conventional Neal-Smith boundaries since they are defined for a class IV fighter and not a class III transport aircraft. Therefore Mooij proposes an alternative bandwidth and revises the previous Neal-Smith boundaries to account for the differences.

Three aspects were considered:

1. The selection of the appropriate time delay for both the pilot and the flight control system;
2. The selection of the Bandwidth for the Neal-Smith analysis;
3. The determination of maximum closed loop resonance value.

Mooij found that a 0.3 second pilot time delay was appropriate for the modified criterion. He also found the variation in compensation with different pilot bandwidths (1.2, 1.4 and 1.6 rad/s) and with well behaved aircraft was low, hence demonstrating a lack of flying qualities cliff (or rapid degradation in flying qualities). The pilot compensation required for the two larger bandwidths expressed in terms of lead time constant was found to exceed 1 second, which was considered to be the limit for Level 1 qualities. Hence 1.2 rad/s was chosen as the minimum required bandwidth. The revised boundaries modified the original boundaries (see figure 4.19) by reducing the maximum phase lead to 50 degrees, and reducing the maximum closed loop resonance.

4.9.3 Advantages and Disadvantages of the Neal-Smith Criterion

Aircraft with desirable characteristics exhibit essentially constant pilot phase compensation for a relatively wide range of Neal-Smith bandwidths. Poor aircraft exhibit large changes in closed loop performance for small changes in bandwidth which is known as a flying qualities cliff. The Neal-Smith criterion is generally a good discriminator between good and poor aircraft, except for aircraft with low short period damping ratios where it may be observed that the pilot phase compensation value becomes very dependent on the chosen Neal-Smith bandwidth, especially for poor aircraft.

However, the Neal-Smith criterion is also dependent on the use of a pilot model. There are many possible pilot models which may be used and the model is also dependent on the aircraft class and task under consideration. In addition, iteration is required to obtain the pilot compensation values and therefore an automated process is used.

4.9.4 The Application of the Neal-Smith Criterion to the Present Work

The Neal-Smith criterion is used with this work for analysis of the flight control system control law response characteristics, though it is not explicitly used as a design criteria. An automated routine was used to obtain the pilot phase compensation values since iteration is required, along with a certain amount of trial and error.

4.10 Flying and Handling Qualities Regulations and Requirements

The contents of the three main flying qualities documents are briefly described within. These documents are MIL-STD-1797A [66], the main US DoD document for military aircraft, and JAR 25 and FAR 25, which are the European / US civil large aircraft requirements respectively. In addition, MIL-F-8785C is also described which is the forerunner to MIL-STD-1797A.

4.10.1 DEF STAN 00-970

DEF STAN 00-970 [79] is the UK Defence Standard for military aircraft procurement. It contains a series of statements concerning the design requirements for aircraft, although only the handling and flying qualities requirements are considered here. The flying qualities requirements include constraints on:

- The Control Anticipation Parameter (CAP) criterion is given for different aircraft classes and flight conditions;
- Limits are placed on the stick force per g;
- Limits are placed on the short and long term mode damping requirements;
- Trim characteristics;
- 'Suitability requirements', i.e. the response characteristic must be suitable to the task for which it is intended.

4.10.2 MIL-F-8785C

The MIL-F-8785 series were the forerunners to the later MIL-STD-1797A, and also provided the basis for the UK flying qualities document DEF STAN 00-970 [79]. MIL-F-8785C was the latest edition, published in 1980 [53].

- Limits are placed on the short period mode damping ratio;
- Limits are placed on the short period mode frequency through application of the CAP criterion;
- Limits are placed on the phugoid characteristics;
- Limits are placed on the delay in the aircraft response;
- Limits are placed on the longitudinal control force / displacement characteristics;
- Limits are placed on the flight path / airspeed relationship;

Aircraft with non-classical response characteristics are not considered.

4.10.3 MIL-STD-1797A

MIL-STD-1797A [66] is the US DoD Military Standard for handling and flying qualities of Military Aircraft. It contains many criteria, which include the following:

- Control Anticipation Parameter (CAP), in combination with Low Order Equivalent Systems (LOES). This takes the aircraft response transfer functions, and 'matches' them to an effective classical aircraft response. Limits are placed on the amount of mismatch. This is then used by the CAP criterion to determine if the (possibly non-conventional) response meets the CAP requirement;
- Limits are placed on the equivalent time delay for the aircraft;
- Limits are placed on the $\omega_{sp}T_{\theta_2}$ requirement;
- Limits are placed on the short period mode damping ratio;
- Limits are placed on parameters of the pitch rate time response, such as pitch rate overshoot, and initial time delay;
- The product of the control force gradient in steady manoeuvring flight Fs/n and the maximum frequency response amplitude ratio of pitch acceleration to pitch control force $|\ddot{\theta}/Fs|_{max}$ shall not exceed published (CAP) limits;
- Limits are placed on the Bandwidth (flight path and pitch attitude) through the bandwidth criterion;
- A modified Neal-Smith criterion is considered, which looks at acceptable pilot compensation;

- Gibson's Criteria, which consider the nature of the time response, in terms of pitch attitude dropback and the nature of the initial pitch rate response.

4.10.4 JAR 25 and FAR 25

JAR 25 [80] and FAR 25 [81] contain the following criteria:

- A control forces criterion (25.143), limiting the maximum forces which may be applied in any axis;
- A static stability criterion (25.173), which places a requirement on the return to airspeed nature of the aircraft;
- A short period damping criterion (25.181) which states that the mode must be heavily damped.

These are obviously very much more limited in their definition, and little detail is included with the criteria themselves.

The MIL-STD is by far the most comprehensive document, and the design criteria used within this program are contained within it. However, some of the requirements are currently too lax, and a revision is currently under production.

The JAR / FAR requirements are very much more limited, and are restricted solely to aircraft with classical response types, whereas the MIL-STD may be applied to both classical and non-classical response types.

5 Extended Investigation of Flying Qualities Criteria Against Past Research Programmes

This Chapter describes a theoretical study used to analyse the results of previous studies to a new set of criteria in order to ascertain whether any trends have been missed.

5.1 Introduction

The databases considered were all from flying qualities research programmes involving civil aircraft, primarily in the approach and landing task.

Flying qualities data from a number of published reports were assessed against the set of flying qualities criteria discussed in Chapter 4. The object was to compare the results from the past experiments to determine whether the results are consistent, and to formulate a series of requirements for flying qualities in the approach and landing task.

There is also a brief comparison of the results from fixed and moving base simulators, specifically comparing the results from fixed base simulators, moving base simulators and in-flight simulators.

The majority of the studies examined have been flown using transports of the 100 to 150 seat range, i.e. having a mass of between 100,000 and 200,000 lbs. However, some studies have been carried out using larger aircraft, of up to 1,000,000 lbs mass. The results obtained from these trials will also be discussed. All of the studies contained within this component of the work meet the following criteria:

- The reports which document the studies are in the public domain;
- It is possible to reproduce the aircraft response characteristics using the information contained within the reports;
- The data was relevant to this programme, i.e. a civil transport aircraft was considered, although some variation in aircraft mass was permitted.

Therefore, the studies in table 5.1 were identified. Individual studies which were carried out as a result of a larger program have been grouped together. There are other data sources available, but time and computing constraints precluded their use for this work. VMS refers to the motion simulator at NASA Ames, and TIFS refers to the USAF Total In-Flight Simulator.

Database	Weight	Type of Simulator
Field Thesis	65,000 lbs	Fixed Base
Field 9401	65,000 lbs	Fixed Base
Mooij	64,000 lbs	NLR Motion Sim & TIFS
NASA TR 80 3067	350,000 lbs	Motion Sim
McDonnell IRAD		
AIAA 93-3815	141,200 lbs	MD-80 Simulator
AIAA 93-3816	500,000 & 750,000 lbs	TIFS
AIAA 94-3489	500,000 & 750,000 lbs	VMS & TIFS
AIAA 94-3510	500,000 lbs	VMS

Table 5.1: Summary of Database Characteristics

5.2 Flying Qualities Criteria Used for Analysis

The following criteria were used to analyse the response characteristics. The criteria are described fully within Chapter 4 of this thesis.

- The Control Anticipation Parameter;
- The Generic Control Anticipation Parameter;
- Gibson's Pitch Attitude Dropback Criterion;
- Gibson's Phase Rate Criterion;
- The Neal-Smith Criterion;
- The Bandwidth Criterion;

Much use was made of Matlab [82] routines to analyse the data. The pitch rate and normal acceleration transfer functions for the augmented aircraft were entered as Matlab script, and the response characteristics of these transfer functions verified against the published response characteristics in the appropriate report to ensure that the aircraft models described within the reports have been accurately reproduced.

A number of routines were written by the author in Matlab to perform the flying qualities analysis of the aircraft. In addition, a number of routines contained within the Interactive Flying Qualities Toolbox [83] for Matlab were used or modified.

The results for these studies have been included in appendix B. The results consist of a series of figures showing the characteristics of the augmented aircraft plotted against Cooper Harper rating. The Cooper Harper rating is described within section 4.1.1 in more detail.

For each individual study, two figures are presented. These contain the following information:

- Plot Set 1: Plots of CAP, GCAP, dropback, time delay, short term mode natural frequency and T_{θ_2} versus Cooper Harper rating;
- Plot Set 2: Plots of Phase Rate, Crossover Frequency, pitch attitude bandwidth, Neal-Smith phase compensation value, Flight path angle bandwidth at the centre of gravity and flight path bandwidth at the pilot's station versus Cooper Harper rating.

5.3 Analysis of Field's Work

The work carried out by Field considers a Generic Regional Aircraft being flown in the approach and landing task and is described in references [4] and [84].

A number of different control law concepts were designed using pole placement methods (see section 6.1.2), and then evaluated in the British Aerospace Engineering Flight Simulator at Woodford (which was also used for the flying qualities evaluations described within this thesis and described in section 7.1.

The evaluation task used for these evaluations consisted of an approach and landing task, at constant airspeed, using an offset ILS to give the pilot a correction to make when close to the runway. In addition, a gust was injected to further 'excite' the aircraft.

Data from two individual studies has been used here. The first [84] considers a number of control laws which have been designed using a pole placement strategy in a similar manner to the study described in reference [85], see section 6.1.2. The second study [4] looks at aspects of the aircraft pitch response such as pitch sensitivity and short term mode characteristics, in greater detail.

5.3.1 The Results of the Analysis of Field's Work

The figures containing these results of the analysis of Field's thesis work are shown in figures B.21 to B.26. Analysis of the data leads to the following conclusions:

- The rate demand response characteristics with the best Cooper Harper ratings both had GCAP values of approximately 0.6 $rad/s^2/g$. One of these aircraft was flight path rate demand and the second was an angle of attack demand. There was one other aircraft with a Cooper Harper rating of 2 was a flight path angle at pilot station demand, but this law does not have rate-like characteristics;

- The phase rate criterion was met by all of the aircraft tested;

- The best aircraft had a pitch attitude bandwidth of between approximately 1.5 and 3 rad/s;

- The aircraft with proportional-plus-integral control law strategy were generally rated worse than the aircraft with a pole placement control law strategy due to the pronounced floating tendency in the flare (where the aircraft flies just above the surface of the runway for a considerable part of the length of the runway);

- The slower aircraft with flight path rate demand response characteristics and the lower short term mode natural frequencies but with medium to high GCAP value had better Cooper Harper ratings than the faster flight path rate aircraft with the high GCAP value.

The figures containing the results of the analysis of Field's Report CoA 9401 [84] are shown in figures B.27 to B.32. The figures demonstrate the following points:

- All of the aircraft were described as being slow and underdamped, despite the augmentation;

- For the angle of attack laws, the spread of CAP values for the laws with the best Cooper Harper ratings is greater than the spread for the laws with the best GCAP ratings;

- For the pitch rate demand laws, the best Cooper Harper ratings occur for aircraft with Neal-Smith compensation values of between 10 and 30 degrees of pilot lead required. Outside these parameters, the Cooper Harper ratings are degraded;

- For the aircraft with pitch rate demand response characteristics and a P+I control law design strategy, the Cooper Harper ratings improve as the dropback value increases from -0.4s through to 0.4 seconds. The laws have a reasonably constant GCAP value (around 0.5 $\pm$ 0.1), and it is interesting to note that the opposite trend can be seen in Neal-Smith assessment since, as the required pilot compensation value changes from 5 degrees of lead through to 15 degrees of lag, the Cooper-Harper ratings steadily improve;

- For the aircraft with pitch rate response characteristics, the optimal dropback values are around -0.5 seconds, with the best GCAP value being around 0.3 $rad/s^2/g$. The aircraft with the higher GCAP values and the positive dropback values received poorer Cooper Harper ratings, due to poor flight path control and a floating tendency in the flare. It is possible that the pilot may have stated that the flight path control posed a problem based on the flare characteristics, and it is not known how the pilots rated the approach alone.

5.3.2 The Discussion of the Results of Field's Work

The best aircraft with rate demand response characteristics both had GCAP values of approximately 0.6 $rad/s^2/g$. One of these aircraft had flight path rate demand properties and the second had classical response characteristics.

The phase rate criterion was met by all of the aircraft tested, which is not surprising since there were no significant high order dynamics or time delays present.

The aircraft with proportional-plus-integral (P+I) controller design strategies were generally rated worse than the aircraft with pole placement design strategies due to the pronounced floating tendency in the flare. This is expected since the aircraft with P+I controllers will hold pitch attitude accurately, whereas the pole placement aircraft will not hold the pitch attitude as tightly during the flare due to the lack of integral action. This demonstrates that an aircraft with a pole placement controller has slightly different characteristics to the the same baseline with a P+I controller, even though they may be designed to the same design criteria.

The slower flight path rate aircraft with the lower short term mode natural frequencies but with medium to high GCAP value was rated better than the faster flight path rate aircraft with the high GCAP value. This demonstrates that for these two aircraft, the GCAP value may be more important than the short term mode natural frequency.

All of the aircraft evaluated were described as being slow and underdamped, despite the presence of augmentation. Hence it is thought that pole placement augmentation may not be having the desired effect on the aircraft flying qualities.

Better ratings are also found when a small amount of Neal-Smith lag is required. As before, this may be due to the fact that the pilot expects to apply a slight amount of phase compensation when flying transport aircraft.

Finally, for the aircraft with non-conventional response characteristics, it is important to consider that some of the evaluation pilots here had not flown non-conventional aircraft before. These may require a different piloting technique, and they can sometimes surprise the pilot. If a pilot expects an aircraft to fly like a classical aircraft, he may rate unconventional aircraft worse.

5.4 Analysis of Mooij's Work

This study [62] considers a number of pitch rate response types which were evaluated for a transport aircraft in both a moving base simulator and also in the USAF TIFS in-flight simulator. An ILS approach task was studied. The aircraft evaluated in the ground based and in-flight simulation were identical.

Finally, this was the only study which considered the use of direct lift control (DLC), which may be used to modify the lift curve slope, or to displace the aircraft in heave without pitching. This therefore effectively considers a controllable T_{θ_2}.

5.4.1 The Results of the Analysis of Mooij's Work

The results of the analysis of Mooij's work are shown in figures B.33 to B.36. The figures demonstrate the following points:

- The analysis of Mooij's results shows that for the aircraft without Direct Lift Control, there is a 'best' value of Generic CAP at approximately 0.25 $rad/s^2/g$. In addition, there is also a 'best' value of dropback at approximately -0.5 seconds. These combine to give a best value of Neal-Smith pilot phase compensation at around 25 degrees of lead.
- All of the aircraft have suitably low values of phase rate, at around 90 to 110 degrees/Hz;
- The 'G' series of results show that as the $1/T_{\theta_2}$ value increases, i.e. the T_{θ_2} value decreases, the Cooper Harper rating improves for otherwise constant dynamics (i.e. constant short term mode characteristics);
- Other effects due to DLC are more confused. Again, looking at the results from the analysis of the aircraft G1 to G4, there is no variation in CAP, GCAP or any of the flight path bandwidth values, although there is a very small increase in pitch attitude bandwidth and Neal-Smith pilot compensation requirement. However, these changes are very small, and may be considered to be insignificant;

5.4.2 The Discussion of the Results of Mooij's Work

The Mooij study is interesting since it describes the use of Manoeuvre Enhancement by means of Direct Lift Control (DLC). This is important data since it enables the relationship between flight path and pitch attitude to be varied, i.e. the 'effective' lift curve slope may be varied. These aircraft with Manoeuvre Enhancement are referred to in Mooij's thesis as 'G' aircraft. Manoeuvre enhancement is implemented through deploying the spoilers, with the spoiler demands being passed through a washout filter.

Since the relationship between pitch attitude and flight path angle is broken by the DLC, the actual value of $1/T_{\theta_2}$ may need to be modified to account for the DLC. As stated earlier, the T_{θ_2} value represents the time delay between the pitch attitude and flight path angle responses, and DLC modifies this relationship.

The 'G' aircraft results show that as $1/T_{\theta_2}$ increases (or T_{θ_2} decreases), the Cooper Harper rating improves for otherwise constant dynamics (i.e. constant short term mode characteristics). This is due to the initial 'spike' in the flight path rate response which gives 'lead' in the flight path independently of lead in the pitch attitude response (which serves to increase the pitch attitude dropback). However, the steady state normal acceleration response is demonstrated to be identical for each of the aircraft. Control Anticipation Parameter in its classical form is the initial pitch acceleration divided by the steady state normal acceleration. Therefore if this steady response is unchanged and the initial pitch acceleration is unchanged, the CAP theory states that the Control Anticipation Parameter value should be unchanged.

Other effects due to DLC are more confused. Again, looking at the results from the analysis of aircraft G1 to G4, there is no variation in CAP, GCAP or any of the flight path bandwidth values, although there is a very small increase in pitch attitude bandwidth and Neal-Smith pilot compensation requirement. However, these changes are very small, but may be considered to be significant.

5.5 Analysis of McDonnell Douglas Internal Research and Development (McAir IRAD) Work

The studies referred to within this section were produced by McDonnell Douglas Internal research and development programmes. Several studies were considered [86, 87, 88, 89, 90]. They consider a mixture of evaluations carried out in both the USAF TIFS and a McDonnell Douglas MD83 flight training device (moving-base ground-based simulator). These studies consider variations in short period mode natural frequency, centre of rotation position and time delay. The five reports used are summarised here.

AIAA Paper 93-3815 [88]

The aircraft used for this study is an advanced technology transport aircraft at a weight of 141,200 lbs. A number of different ILS-based tasks were considered. A MD-80 motion base simulator was used for the evaluations. The evaluation programme considered a number of different classical response aircraft, with varying the short period characteristics and the time delays.

AIAA Paper 93-3816 [89]

The aircraft used for this study was a generic advanced technology transport aircraft at a weight of either 500,000 lbs or 750,000 lbs. The task used was an offset approach and landing task from an ILS approach. The TIFS in-flight simulator was used for the evaluations. The evaluation programme considered a number of different classical response aircraft, with varying the short period characteristics and the aircraft time delays.

AIAA Paper 94-3489 [86]

The aircraft used for this study was a generic advanced technology transport aircraft at a weight of either 500,000 lbs or 750,000 lbs. The task used was an offset approach and landing task from an ILS approach. Both the TIFS in-flight simulator and the NASA Ames VMS ground-based motion simulator were used for evaluations. This evaluation programme considered a number of different classical response aircraft, with varying the short period characteristics and the time delay.

AIAA Paper 94-3510 [87]

The aircraft used for this study was a generic advanced technology 500,000 lb transport aircraft. The task used was an offset approach and landing task from an ILS approach. The simulator used was the NASA Ames VMS motion simulator. The evaluation programme considered a number of different classical response characteristics, by varying the short period characteristics and the pilot position ahead of the instantaneous centre of rotation.

AFWAL TR-80-3067 [90]

This study was performed by McDonnell Douglas in order to obtain data to support the criteria in MIL-F-8785B [91] for Class III (transport) aircraft. This programme was designed to look at both conventional and relaxed static stability aircraft.

Both longitudinal and lateral/directional flying qualities were studied, although this study only considers the longitudinal flying qualities aspects of the work. The study was performed in a six axis motion base simulator using a 350,000 lb aircraft model performing an ILS approach and landing task. A total of 42 aircraft were examined

- some were based on a typical wide body transport aircraft, with varying centre of gravity positions.

A total of 5 test pilots performed 154 evaluations of the 42 aircraft. Each approach commenced 7.4 miles from the touchdown point at a height of 1500 ft on the extended centreline. The pilot was briefed to maintain altitude until the glideslope was intercepted, and then to fly down the glideslope. The pilot was required to fly on instruments in cloud until he broke out at 700 feet AGL for a visual landing. The test was performed in a turbulent atmosphere.

5.5.1 The Results of the Analysis of the McAir IRAD Work

AIAA 93-3815

The results of the analysis of the data within the report AIAA 93-3815 are shown in figures B.17 to B.18. The figures demonstrate the following points:

- There is an improvement in pilot rating as the dropback value increases from -1.5 seconds through to -0.5 seconds;
- The only Level 1 aircraft had a Neal-Smith phase compensation of around 42 degrees of lead. As the time delay was increased, the required compensation increased steadily to 80 degrees of lead for the worst aircraft;
- The higher value of GCAP (0.27 $rad/s^2/g$) tested gave the better flying qualities ratings;
- Of the two low phase rate aircraft (under 100 deg/Hz), the better aircraft had the higher GCAP rating. All of the poor aircraft (i.e. higher time delay) had much larger values of phase rate;
- The range of short period mode natural frequencies do not have any positive trends;
- A longitudinal response time delay greater than 125 msec has a large impact on Cooper Harper ratings, with the larger the delay, the poorer the rating.

AIAA 93-3816

The results of the analysis of the data within the report AIAA 93-3816 are shown in figures B.19 to B.20. This work demonstrates the following points:

- There is an improvement in CHR as the dropback increases from -1.5 seconds to 0.5 seconds, with the best ratings having a dropback value of 0.5.seconds;

- The aircraft with a GCAP rating of 0.6 $rad/s^2/g$ to 0.7 $rad/s^2/g$ are rated better than those with lower GCAP values;
- There is no specific benefit through having either a high or low T_{θ_2} value;
- The higher short period mode natural frequencies give better ratings than those with lower frequencies, corresponding to the aircraft with a higher bandwidth and higher crossover frequency;
- The aircraft with lower time delays have better Cooper Harper ratings than those with higher time delays;
- Good aircraft have a Neil-Smith phase compensation of below 50 deg, with the best aircraft having no requirement for compensation. Poor aircraft with small values of phase compensation have large values of the phase rate parameter;
- A phase rate value greater than 150 deg/Hz has a detrimental effect on Cooper Harper rating.

AIAA 94-3489

The results of the analysis of the data within the report AIAA 94-3489 are shown in figures B.11 to B.14. The figures demonstrate the following points:

- When considering the motion simulator (VMS) work, there are less visible trends than with the TIFS work;
- As the value of pitch attitude dropback increases from -1.5 s through to 0.5 seconds, the Cooper Harper ratings improve for the TIFS evaluations. In addition, a similar trend is visible with the values of CAP and GCAP, with the best control laws having a CAP value of 0.5 $rad/s^2/g$, and a GCAP value of 0.6 $rad/s^2/g$ to 0.7 $rad/s^2/g$;
- The Neal-Smith phase compensation values give better ratings as the required phase compensation changes from lead towards zero. More than 40 degrees of compensation give aircraft evaluated in the TIFS Level 2 flying qualities;
- As the pitch attitude bandwidth and the crossover frequency increase, the Cooper Harper ratings improve for the TIFS evaluations;
- An aircraft phase rate greater than 200 deg/Hz give Cooper Harper ratings worse than Level 1 for the TIFS evaluations;
- The VMS results do not show any significant trends, except that the best aircraft has a GCAP value of 0.2 $rad/s^2/g$, a Dropback value of -0.8 seconds and requires a significant amount of Neal-Smith phase compensation.

AIAA 94-3510

The results of the analysis of the data within the report AIAA 94-3510 are shown in figures B.15 to B.16. The figures demonstrate the following points:

- As the centre of rotation position is moved, the value of $1/T_{\theta_2}$ changes. The one clear trend that can be seen is that as the value of $1/T_{\theta_2}$ decreases, the Cooper Harper ratings improve. For a constant value of CAP, i.e. short period mode natural frequency, the Cooper Harper ratings can be seen to improve as the pilot's position moves forward;
- The trends indicated in this work are generally confusing.

NASA TR 80-3067

The results of the analysis of the data within the report NASA TR 80-3067 are shown in figures B.37 to B.38. The figures demonstrate the following points:

- The best ratings are for aircraft with GCAP value of 0.2 $rad/s^2/g$ and a dropback value of -0.8 seconds. As the GCAP and dropback values diverge away from these values, the ratings worsen;
- The best aircraft have a pitch attitude bandwidth of 0.7 rad/s, a Neal-Smith phase compensation of 50 deg of lead, a crossover frequency of 3 rad/s and a flight path bandwidth of 1.3 rad/s. As before, there are also aircraft with these criteria values with worse ratings.

5.5.2 The Discussion of the Results of the McAir IRAD Work

An improvement in Cooper Harper was generally shown for increasing GCAP and bandwidth values. For the TIFS work, the best aircraft had the higher GCAP and pitch attitude bandwidths. There is likely to be an upper limit above which an aircraft would appear to be abrupt, but it was not found in these studies.

In addition, specifying a CAP and Dropback value is not sufficient for good flying qualities. It is necessary to consider the aircraft time delay, or phase rate as well. Obviously GCAP does not consider time delay from its definition, and therefore a criterion which addresses this is required.

The value of pitch attitude dropback measured was taken to include the time delay. Since an increasing time delay reduces the dropback value, dropback may account for some time delay effects. However, the magnitude of this effect is not great, and therefore it is likely that a pilot will experience an excessive time delay in terms of phase rate before he experiences a poor dropback value. In addition, poor aircraft with small values of phase compensation have large values of the phase rate parameter. Hence the Neal-Smith criterion does not seem to reflect large time delays enough to exclude such aircraft.

Generally, for the TIFS evaluations, GCAP, CAP, Neal-Smith phase compensation values, pitch attitude dropback and both pitch attitude and flight path angle bandwidth can all be used to discriminate good and bad aircraft with appropriate dynamics, excluding the effects of time delay. However, a limit must also be placed on phase rate or absolute time delay to ensure that the aircraft do achieve Level 1 ratings. Phase rate and time delay cannot be used by themselves since aircraft with wildly differing values of GCAP, CAP and Neal-Smith compensation may have almost identical values of phase rate. These trends were less apparent in the motion simulator evaluations.

In addition, since this study comprised solely aircraft with classical response characteristics, with conventional short period and phugoid modes and a limited range of lift curve slopes, short period mode natural frequency may also be used as a discriminator since CAP is directly related to short period mode natural frequency. For aircraft where the short term mode is independent of the GCAP value due to the effects of lead and lag the short period mode may not be such a good discriminator.

For some of the larger aircraft evaluated in a motion base simulator, the pilot seems to prefer larger amounts of lead compensation, i.e. a more sluggish aircraft. This may be due to the effects of the type of simulator, as large amounts of lead compensations were only rated well in a moving base simulator, or alternatively the pilots may have been expecting a sluggish aircraft.

For the aircraft where the centre of rotation position was varied, the ratings can be seen to improve as the pilot's position moves forward. This suggests that for this particular trial, pilots improved their rating as they received more of an acceleration cue, for a constant short period mode natural frequency.

5.6 Implications of the Results

5.6.1 In-Flight Simulation / Ground Based Simulation Comparison

In comparing the data from all of the studies, it is interesting to plot all of the results from the aircraft evaluated in an in-flight simulator together on the same set of axes, see figures B.3 to B.4. All of the results from the aircraft evaluated in a ground-based motion base simulator are plotted on figures B.1 to B.2 and finally all of the results from the aircraft evaluated in a ground-based fixed base simulator are plotted on figures B.5 to B.6.

This data shows that there is a definite 'best aircraft response characteristic' for in-flight simulation studies with a dropback value of around 0.5 seconds, and with a best GCAP value of around 0.6 $rad/s^2/g$. Although there are good aircraft outside these bounds, they are few in number. In addition, the required Neal-Smith pilot phase compensation is generally between 10 degrees of lag and 20 degrees of lead for the best aircraft. However, for motion-base ground simulators, the best GCAP value is around 0.2 $rad/s^2/g$ to 0.25 $rad/s^2/g$, and a dropback value of between -0.5 seconds and -1.0 seconds (i.e. overshoot), and the required Neal-Smith pilot compensation is between 30 and 50 degrees of pilot lead required. The low dropback trend for moving base simulation is also seen within reference [2] for fighter aircraft.

Comments obtained from test pilots indicate that they tend to overdrive aircraft in fixed base simulators due to the lack of motion cues. One of the principal differences between the results presented in the previous paragraph for the best aircraft, indicates that pilots tend to prefer to overdrive the best aircraft more in a ground-based moving base simulator compared to in-flight simulators.

In addition to this, pilots naturally feel more anxious in in-flight simulation. It is therefore suggested that they may rate an aircraft badly if it is being evaluated in an in-flight simulator whereas the same aircraft would not be downgraded in ground based simulators since they can accept the fact that they need to overdrive the ground-based simulator.

The aircraft which are rated best in fixed base ground-based simulator results tend to have characteristics similar to those which are rated best in an in-flight simulator. Certainly, the results from the current program of research [58, 92] and also the past programmes performed by Field [4] demonstrate that the required pilot Neal-Smith phase compensation values, dropback ratings and GCAP ratings are more comparable with the same characteristics for good in-flight aircraft compared to the characteristics required for aircraft which perform well in motion base ground-based simulators. This may be due to the fact that the pilot can tolerate the absence of motion cues and will not attempt to overdrive the motion system to get desirable motion characteristics. However, it is very easy for the pilot to fly a aircraft very tightly in a fixed base ground-based simulator and not to be aware of it, so great care must be taken here.

Criterion	Desirable Value for...		
	In-Flight Simulation	Moving Base Simulation	Fixed Base Simulation
GCAP / $rad/s^2/g$	0.6-0.7	0.25	0.3-0.6
Dropback /s	0.5	-0.6	-0.8 - 0.8
Phase Rate /deg/Hz	100	100	Not Known
Pitch Att Bandwidth /rad/s	1.3	0.8-1.3	1.1-2.2
Flight path Bandwidth /rad/s	0.55-0.75	0.4-1.1	0.4-1.1
Neal-Smith Phase Comp /deg	5 lead - 20 lag	30-50 lag	20 lead - 30 lag

Table 5.2: Flying Qualities Design Requirements for the ILS Approach and Landing Task

5.6.2 Flight Control System Control Law Design Requirements

From the results presented above, it can be seen that there are aircraft which are rated better than others for the ILS approach and landing task. Therefore, it may be seen that there are values of the flying qualities criteria considered which are more suitable than others for this task. The suitable values of some of the flying qualities criteria, i.e. those which give the best Cooper Harper ratings have therefore been presented in table 5.2.

Note that there are differences between the ideal design points for the in-flight simulation, moving base ground simulation and fixed base ground simulation. Looking at the above requirements shows that the requirements for in-flight and moving base ground simulation are significantly different with overlap between the two for fixed base simulation. It must be remembered that the fixed base simulation in this case had a night visual scene, and therefore the results may be different with a higher fidelity visual system. It is also said that once a PIO has been detected in flight, increasing the simulator fidelity improves the likelihood of detecting PIOs [47].

5.7 Summary Conclusions of the Investigation

The following comments may be made concerning the criteria:

- The trends seen in in-flight simulation results are more pronounced compared to those from moving base simulation results as the configurations with the best Cooper Harper ratings lie within a smaller range;

- The use of moving base simulation for flying qualities trials is under question, as the aircraft with the best Cooper Harper ratings have significantly different characteristics compared to the aircraft with the best Cooper Harper ratings from in-flight simulation trials. The use of a fixed base simulator gives a certain amount of overlap between the two, though this may depend on the fidelity of the simulator;

- GCAP may be used to assess flying qualities and is applicable to non-conventional response types. GCAP is more applicable than CAP since the approximation behind CAP is only applicable to a classical aircraft, and the GCAP results are consistent across a number of different control law types;

- Pitch attitude dropback is an important consideration, and the pilot will see whether a particular aircraft has dropback or more importantly overshoot, but dropback is not suitable for assessing time delay;

- Phase rate seems to be a suitable criterion for assessing the effects of time delay, since a delay will have a serious effect on it;

- Bandwidth is a consideration, and will discriminate between good and bad aircraft, though it is not as sensitive to the effects of time delay as phase rate;

- Neal-Smith reflects changes in time delay alone, with larger phase compensation values required as the time delay increases. However, the change in phase compensation is insufficient to preclude that aircraft for an aircraft with otherwise good dynamics;

- Since most of the aircraft considered for this study are either classical or have rate-like characteristics, it is difficult to recommend which is the best response type. However, aircraft with unconventional response characteristics may be used with the criteria described here.

6 Flight Control Law Design Methods

This Chapter describes the flight control law design aspects of the work. The different methods for augmenting the aircraft control response characteristics are considered first. Then a brief description of the issues relevant to the control law design criteria are presented and finally, the design criteria used to specify the control law requirements are given.

Since there are many different ways to specify the control law response characteristics, an attempt was made to specify desirable characteristics in a way which is independent of the control law being designed. Therefore a number of 'law independent' criteria were specified which captured all of the major characteristics of a particular response, these are discussed further in section 6.3.

6.1 Controller Strategies

There are many different types of controller design strategy in use. Some are easier to implement than others, and some are more suitable for a specific application. The controller strategies considered here are pole placement, lead-lag compensation and proportional plus integral (P+I) control. These were selected because they are common and readily understood strategies which have been demonstrated to be suitable for flying qualities applications. A description of each strategy is presented here.

6.1.1 The Lead-Lag Compensation Strategy

The lead-lag compensation strategy incorporates a lead-lag filter in the command path to apply phase lead or lag compensation at a certain frequency. Since the filter is placed in the command path, it is not in the closed loop path and cannot affect the stability of the aircraft, unless the filter itself is unstable. The location of a typical filter may be seen in figure 6.1.

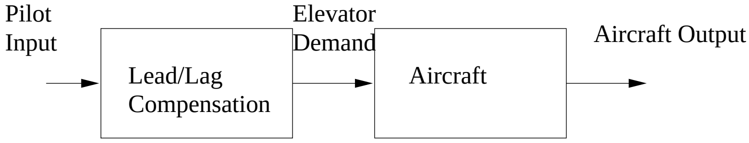


Figure 6.1: The Location of a Lead-Lag Filter in the Longitudinal Command Path

It may be shown that the filter may be used to augment longitudinal flying qualities to good effect. It can be demonstrated that the dropback and GCAP characteristics of a classical aircraft may be modified in a precise manner through the selection of the appropriate filter parameters.

6.1.2 The Pole Placement Strategy

Pole placement methods may be used to modify the locations of the transfer function poles of a classical aircraft. The aircraft states for this work are q, θ, α and U.

This method enables precise specification of all of the closed loop poles provided full state feedback is assumed. The states used are pitch rate (q), pitch attitude (θ), angle of attack (α) and airspeed (U). The procedure defines the loop gains required to achieve the desired closed loop poles. A typical pole placement controller structure may be seen in figure 6.2.

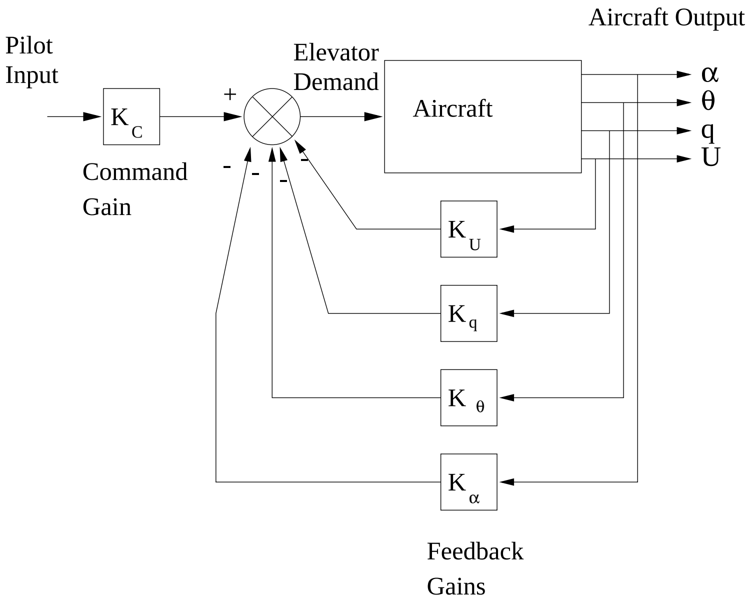


Figure 6.2: The Pole Placement Structure

Many applications use partial state feedback, where some, but not all of the states are fed back to the elevator. This is generally referred to as 'output feedback' since the poles cannot be completely specified. A simple pitch, or yaw, damper is an example of this, where specific properties of the response are modified to make selected improvements.

One of the major problems with pole placement design methods is that they do require the aircraft model to be well defined as minor differences in the aircraft model or flight case may have an effect on the actual law properties. Some of the other methods may be more robust to variations in the aircraft's characteristics.

6.1.3 The Proportional-plus-Integral Controller Strategy

Proportional-plus-integral (P+I) controllers are used for many industrial applications since the controllers are generally straightforward to design, and give good control of the controlled variable without the requirement of feeding back all of the state variables. The integral action generally ensures that the error is reduced to zero, and the use of a feedforward loop can also be used to make a sluggish response crisp through controlling the location of the induced controller zero.

Many methodologies for dealing with P+I controller design exist. For aircraft, a series of linear controllers is designed for a number of different flight cases. The gains used with the controllers may then be scheduled as required to give desirable response characteristics over the entire flight envelope. For these reasons, P+I control was used as the controller strategy for the control laws designed for this work. A typical P+I controller structure is shown in figure 6.3.

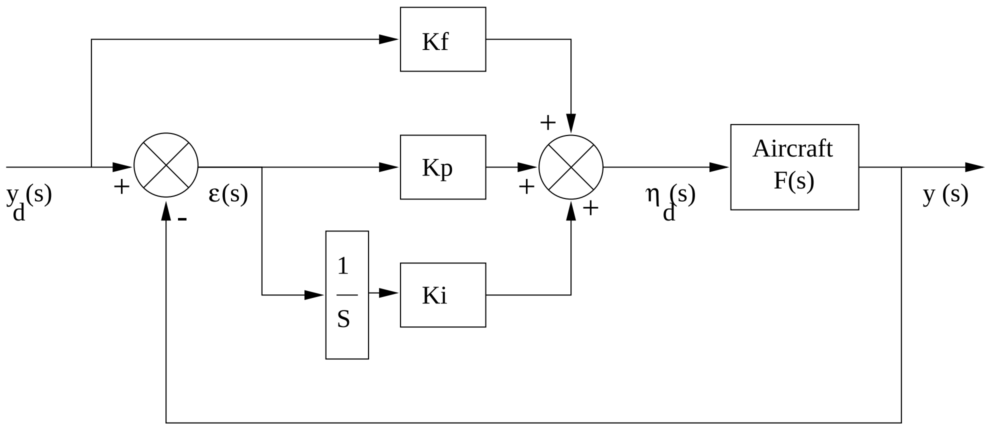


Figure 6.3: Proportional + Integral Controller Structure with Feedforward Path

It can be shown that the controller structure shown in figure 6.3 introduces an additional pole and an additional zero to the closed loop aircraft transfer functions. Consider the controller structure shown in figure 6.3,

$$\eta_d(s) = y_d(s)K_f + \epsilon(s)\left(K_P + \frac{K_i}{s}\right) \tag{6.1}$$

$$y(s) = F(s)\eta_d(s) \tag{6.2}$$

where

$$F(s) = \frac{N(s)}{\Delta(s)} \tag{6.3}$$

$$\epsilon(s) = y_d(s) - y(s) \tag{6.4}$$

Therefore,

$$y(s) = y_d(s)K_f F(s) + (y_d(s) - y(s))\left(K_P + \frac{K_i}{s}\right)F(s) \tag{6.5}$$

Collecting terms,

$$y(s)\left(1 + F(s)\left(K_P + \frac{K_i}{s}\right)\right) = y_d(s)F(s)\left(K_f + K_P + \frac{K_i}{s}\right) \tag{6.6}$$

Therefore, by substituting equation 6.3 and rearranging,

$$\frac{y(s)}{y_d(s)} = \frac{\frac{N(s)}{\Delta(s)}\left(K_f + K_P + \frac{K_i}{s}\right)}{1 + \frac{N(s)}{\Delta(s)}\left(K_P + \frac{K_i}{s}\right)} \tag{6.7}$$

which can finally be arranged as

$$\frac{y(s)}{y_d(s)} = \frac{N(s)\left(s(K_f + K_P) + K_i\right)}{s\Delta(s) + N(s)(sK_P + K_i)} \tag{6.8}$$

Therefore both the open loop numerator N(s) and denominator δ(s) are raised in order by one. The closed loop denominator will have an additional pole, which is independent of the value of the feedforward gain K_f but dependent on the K_p and K_i gains. The numerator will have an additional zero which is dependent on the value of the feedforward gain K_f as well as one the K_p and K_i gains. The lead-lag properties of the controller may be modified by placing the closed loop pole and zero at specified locations. Hence the benefits of modifying the GCAP and dropback characteristics in a precise manner may also be realised, as with lead-lag command path filtering, but stability augmentation of the aircraft is also simultaneously possible.

6.1.4 The Feedback-Feedforward Controller Strategy

This type of controller design method is essentially similar to the proportional-plus-integral controller design strategy described above. A slightly different approach is made since the feedback loops are designed first so that the aircraft may be stabilised with the aircraft poles having desired values. Following this, the feedforward path is designed to give the necessary compensation for desirable flying qualities.

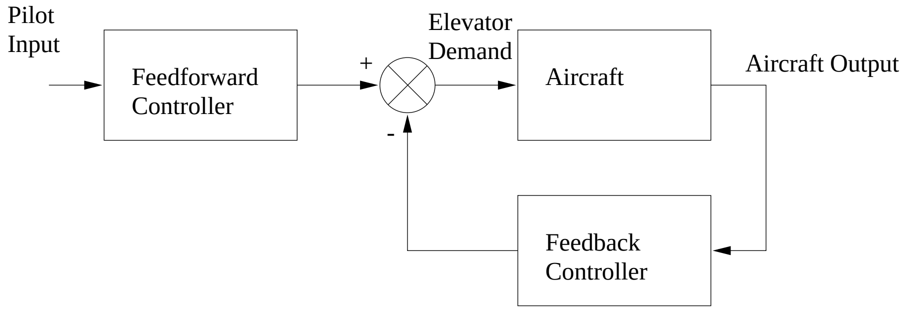


Figure 6.4: A Generic Feedforward-Feedback Controller Structure

The principal difference between this strategy and the usual P+I controller design strategy is that the feedback and feedforward components are designed independently. A typical generic feedback-feedforward controller structure is shown on figure 6.4.

6.2 Flight Control Law Design Criteria Discussion

This section describes how the flying qualities criteria were interpreted for use as control law design criteria. Chapter 5 explained how past aircraft flying qualities evaluations may be analysed using the appropriate flying qualities criteria and trends discovered in those past evaluations. That material is expanded on here by tying these trends together with other related issues. By this means, a series of 'control law independent' design criteria were developed for a generic fly-by-wire regional aircraft for the approach and landing flight phase.

6.2.1 Issues Related to the Aircraft Flight Path Characteristic

Since a pilot is ultimately trying to control an aircraft's flight path, issues related to the flight path characteristic for a given aircraft are important. One good example of a vehicle where quantifiable improvements were made to the flight path characteristics is the Space Shuttle [93]. This is a vehicle with pitch rate response characteristics. Before improvements were made to the Shuttle, closed loop, pilot-in-the-loop control was very difficult. An improvement in the Shuttle flying qualities was obtained when the pitch attitude dropback was increased (note that the definitions of dropback and overshoot vary in reference [93] compared to those of Gibson. The terms used in this thesis are those defined by Gibson). The increase in pitch attitude dropback gives a decrease in flight path time delay. NASA pilots found that the improvements made to the system to enable easier flight path control did not give as much benefit as it did to the non-astronaut pilots. Therefore, it may be inferred that improving the flight path response helps when a conventional piloting technique is being used [93], such as the series pilot model assumed in section 3.2, as opposed to the special technique used by astronaut pilots.

In addition, quickening of the flight path angle display made up for the lack of initial flight path response cues [93], which was the initial problem with the Shuttle.

Heffley [94] shows that for a 'tight' flight path control task, such as a carrier approach task, an improvement in the pilot rating may be obtained by decreasing the flight path time delay, i.e. by increasing the pitch attitude dropback, or by use of direct lift control. This implies that T_{θ_2} cannot be changed through lead-lag filtering since T_{θ_2} specifies the relationship between pitch attitude and flight path angle and is fixed by the aerodynamics of a particular aircraft. Direct Lift Control (DLC) is the only method which may be used to decouple pitch attitude and flight path angle since it provides a change in flight path with no additional pitch attitude change.

Finally, Moorhouse [95] states that landing performance can be improved by decoupling the flight path response from the airspeed responses. This may be achieved with a control law with normal acceleration demand characteristics to control flight path directly, coupled with an autothrottle to control airspeed directly.

6.2.2 Issues Related to the Bandwidth Criterion

As stated before, the pitch attitude and flight path angle bandwidths are strongly dependent on the short period mode natural frequency. Field [4], who used an almost identical aircraft model for his flying qualities studies, shows that the pitch attitude bandwidth needs to be at least 1.3 rad/s and the flight path bandwidth needs to be at least 0.65 rad/s for Level 1 flying qualities. Field found that simply increasing the short period mode natural frequency improved the flying qualities of the aircraft, with a corresponding increase in pitch attitude and flight path angle bandwidth, although he did postulate that there is an upper limit beyond which the flying qualities start to degrade.

The flying qualities design requirements set out in Chapter 5 show that the desired value of pitch attitude bandwidth should be greater than 1.3 rad/s for a transport aircraft evaluated in an in-flight simulator, which compares well with Field's work. It was shown in section 5.6.2 that the flying qualities design requirements for aircraft evaluated in a fixed base simulator are close to those for aircraft evaluated in an in-flight simulator, with aircraft evaluated in a moving base simulator requiring a significantly modified set of design specifications.

The flight path angle bandwidth requirements derived in Chapter 5 specify that the flight path angle bandwidth should be at least 0.55 rad/s for in-flight simulation and at least 0.4 rad/s for a ground-based simulation.

6.2.3 Issues Related to the Control Anticipation Parameter Criterion

The CAP criterion boundaries for transport aircraft in the approach and landing phase are well defined, but there is some dispute about the lower Level 1 value. This value is generally considered to be too low, often resulting in aircraft with low short period natural frequency values which actually give Level 2 flying qualities whilst being categorised in the Level 1 region on the chart [4]. Field [4] recommends that the Level 1 CAP lower limit should increase and a value of about 0.5 rad/s^2/g should give suitable flying qualities for an aircraft with a conventional response characteristic.

The GCAP requirements derived in Chapter 5 show that for in-flight simulation the desired value of the GCAP (or CAP) parameter is between 0.6 and 0.7 rad/s^2/g. When ground based simulation is considered, the desirable values are smaller. The notional design requirement for a fixed base simulator is between 0.3 and 0.6 rad/s^2/g and the requirement for a moving base simulator is about 0.25 rad/s^2/g.

6.2.4 Issues Related to the Pitch Attitude Dropback Characteristic

The requirements for pitch attitude dropback ($\frac{DB}{q}$) set out in Chapter 5 show that for an aircraft evaluated in an in-flight simulator, the desired pitch attitude dropback value is 0.5 seconds. When ground based simulation is considered, the appropriate dropback values are much smaller, with the pitch attitude dropback requirement for an aircraft evaluated in a fixed base simulator being between -0.8 seconds and 0.8 seconds, and the desirable pitch attitude dropback value for an aircraft evaluated in a moving base simulator being about -0.6 seconds.

6.2.5 Issues Related to the Longitudinal Control Forces

The longitudinal control force gradients were initially designed to give an initial pitch acceleration response of 0.6 deg/s^2/lb for a wheel-type controller. For a large aircraft, it is generally accepted that the desirable value for initial pitch acceleration per unit longitudinal control force should be between 0.4 and 0.7 deg/s^2/lb. It has already been found that for the aircraft under consideration, 0.7 deg/s^2/lb is suitable, and being a small class III aircraft at 90,000 lbs weight (compared to 1,000,000 lbs for a future large transport aircraft), it is likely that a suitable initial pitch acceleration should be towards the higher end of the scale.

Use of initial pitch acceleration as a measure of response is justified from several sources. Field considered the use of a specified initial pitch acceleration per unit longitudinal control force and had no adverse comments concerning control forces for the aircraft being evaluated, see references [4, 84]. Research carried out by McDonnell Douglas on a fighter aircraft tracking task considered variation in both CAP and stick force per g which is described here briefly. This work is described in reference [2]. A number of different CAP and stick force per g values were considered for an in-flight tracking task. Figure 8 in the paper, reproduced here as figure 6.5, shows the results together with pilot comments. Fan lines of constant initial pitch acceleration per unit stick force have been added for the purposes of this thesis.

Now CAP may be expressed,

$$CAP = |\frac{F_e}{Nz_{ps}}|_{ss} \times |\frac{\ddot{\theta}}{F_e}|_{init} \tag{6.9}$$

The stick force per g parameter is represented by $|\frac{F_e}{Nz_{ps}}|_{ss}$ in this equation. Therefore the initial pitch acceleration per stick force may be represented by the following equation;

$$|\frac{\ddot{\theta}}{F_e}|_{init} = \frac{CAP}{|\frac{F_e}{Nz_{ps}}|_{ss}} \tag{6.10}$$

AIAA paper [2] states that, as the stick force per g is increased, the ideal value for the CAP parameter is also increased. Equation 6.10 shows that this gives approximately a constant initial pitch acceleration per pound stick force, as the fan lines drawn on figure 6.5 represent. Initial pitch accelerations greater than this resulted in PIO prone aircraft, whilst lower values resulted in sluggish aircraft.

Although the task and aircraft type under evaluation were different from the aircraft type under evaluation here, it is believed that the same principles still apply,

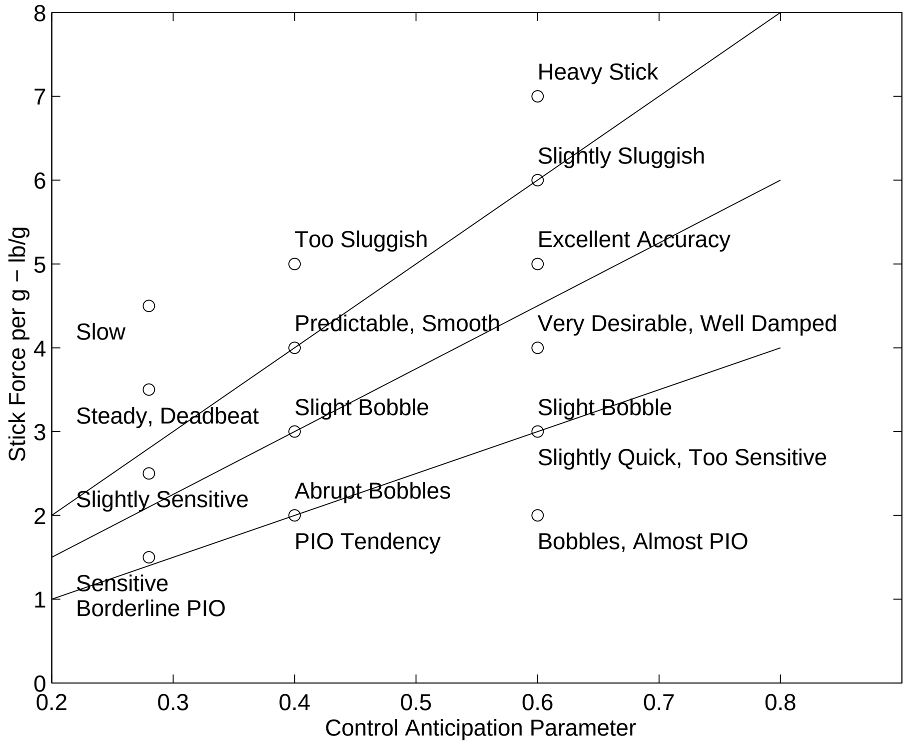


Figure 6.5: Pilot's comments for stick force per g testing (Figure 8 in reference [2]) with lines of constant initial pitch acceleration added

although this cannot be demonstrated conclusively in this thesis due to a lack of data.

6.2.6 Issues Related to the Requirements During the Flare

The flare requirements are different to the approach requirements, since both the airspeed and angle of attack are changing in the flare and it is therefore a non-steady flight condition. In addition, ground effect plays a major part, indeed in large aircraft such as the Boeing 747 and Concorde, it is quite possible to land with little or no flare due to ground effect. For aircraft making carrier landings and for some military aircraft, such as the McDonnell Douglas C-17, making short field landings, the pilot makes no attempt to flare, relying on the aircraft to absorb the high rate of descent.

In a classical civil aircraft, the pilot has to make a rearwards movement of the longitudinal control inceptor in order to flare the aircraft. This is due to the fact that the airspeed is steadily decreasing at a reasonably constant rate once the power has been removed since the pilot is trying to maintain flight path, and this results in an increasing angle of attack requirement if lift is to be maintained. Field [4] states that monotonic forces in the flare are preferred since they give less of a floating tendency as the pilot does not have to continually reverse the direction of movement of the wheel [84]. All classical (non-fly-by-wire) aircraft have monotonic control forces in the flare and this has generally been retained in fly-by-wire aircraft by various means. Monotonic forces ensure that the pilot does not have to adopt a stick pumping technique, i.e. rapidly moving the stick backwards and forwards over the mid-point, and also has implications for feel system design, such as reducing the disturbing effects of 'breakout'. Stick pumping is common for aircraft having rate-like response characteristics in the flare flight phase.

Current fly-by-wire aircraft retain the conventional flare characteristic by, either introducing static stability, or by introducing airspeed stability. A conventional flare requires a rearwards monotonic control input to increase the angle of attack and hence maintain lift. Adopting a pitch attitude response characteristic for the flare gives similar characteristics. Airspeed or static stability also give desirable forces in the flare, again requiring a rearwards monotonic input.

An attitude demand response characteristic has been found to be more suitable than a flight path demand characteristic since, in the flare, the flight path angle is more or less constant, while the aircraft attitude steadily increases to reflect the increasing angle of attack requirement [4].

6.2.7 Issues Related to the Aircraft's Gust Rejection Characteristic

One investigation into large aircraft flying qualities in the approach and flare found that Pitch Rate Command Attitude Hold response type had better flying qualities than the angle of attack command [75], primarily due to the attitude hold capability. This made precise touchdown control easy due to the inherent gust rejection characteristic. These aircraft were also found to be very predictable, which was especially useful with the short aft-tailed aircraft since it did not give as much of a normal acceleration cue due to the centre of rotation effects, in the same way as the Space Shuttle. An identical technique was adopted here as that used to land the Shuttle. The pilots were also impressed with the level turn feature, which removed much of the workload present for the angle of attack response types in maintaining altitude during a turn manoeuvre. When these aircraft were trimmed, and the pilot had the correct thrust setting, they tended to hold airspeed very well, even in turbulence.

6.2.8 Issues Related to the Aircraft's Airspeed Stability Characteristic

A classical aircraft is often referred to as angle of attack demand. This means that if the aircraft is trimmed to a given angle of attack, any variation from this trimmed value is felt by the pilot through tactile feedback from the stick. This characteristic is retained in conventional civil aircraft with power assisted controls through the use of an artificial feel system. Limits are then placed on the airspeed change per unit stick force and the airspeed response characteristic for civil aircraft [81].

Much research has been performed investigating the effects of aircraft airspeed stability on flying qualities. A study performed at NLR in the Netherlands using a piston engine-powered Beech Queen Air [96] concluded that positive stick force stability results in reduced RMS airspeed deviations, reduced maximum deviations from the reference airspeed, and reduced (subjective) pilot effort in airspeed holding. The study was then extended using a Focker F28 MK6000 [97] which investigated varying levels of static stability. This study found that an airspeed force gradient of 5 knots/lb was more desirable than zero or the higher out-of-trim forces required for 2 knots/lb, but these results may have been clouded by the fact that the higher levels of force gradient (2 knots/lb) had a negative long term mode damping ratio (they were mechanised using pitch rate dynamics as the short term mode response characteristic). At low levels of speed stability, there was a modest reduction in airspeed error, at the expense of small increases in glideslope deviations.

Therefore, for the civil flying qualities requirements, static stability is one component of the aircraft's response characteristics. However, aircraft with fly-by-wire do not necessarily have airspeed stability.

Moorhouse [95] considers the apparent phenomenon of losing airspeed stability as the pilot performs a 'tight' glideslope hold task. As described in Chapter 3, aircraft have two longitudinal modes of motion, the short period mode and the phugoid mode. Moorhouse describes how the phugoid mode is modified by the aircraft / pilot closed loop combination to an aperiodic mode, which gives the appearance of losing speed stability. This occurs because the oscillatory phugoid has the effect of returning the airspeed error to zero, while with the aperiodic mode, the airspeed error will never reach zero. Therefore it is inferred that aggressive pitch control by a pilot to control glideslope will cause the appearance of a lack of airspeed stability, and therefore could induce or require more corrective actions in the pitch axis. Moorhouse also demonstrates that the major ambiguity in piloting cues is the coupling between airspeed and flight path responses. He therefore postulates that a more effective control law design could be made by decoupling the airspeed from the flight path response, with airspeed being the reference instead of the angle of attack. The results were validated in a fighter aircraft under a variety of conditions.

Chalk [98] found that increasing the phugoid natural frequency (ω_{ph}) resulted in increased stick force feel for airspeed deviations for constant short term characteristics. In addition, no significant improvements were made to flying qualities for a phugoid damping ratio (ζ_{ph}) greater than 0.15. Rynaski [99] states that a phugoid-like response is crucially relevant in longitudinal flying qualities, especially the angle of attack, airspeed and pitch attitude residues in the phugoid mode, see figure 3.2. It is likely that the flight path residue in the phugoid mode is important when the aircraft nears the ground - in the Sioux City DC-10 accident, the aircraft was near the bottom of the phugoid when it hit the ground, although it could not be said that the aircraft was under conventional control at this point!

The attention required for manual airspeed control and the effect of the aircraft's autothrottle must also be considered, together with the associated pilot situational awareness issues. Airspeed control problems may contribute to a large component of the degraded flying qualities ratings, even when there are no longitudinal pitch control problems [75].

6.3 Flight Control Law Independent Design Criteria

In order to design the longitudinal flight control laws, the following law independent design criteria have been developed. They are intended to provide a series of design requirements for a fly-by-wire transport aircraft in the approach and landing flight phases and they are applicable to aircraft with both classical and non classical rate-like response characteristics. The design values have been derived from the the investigation described in section 5.6.2 and section 6.2 and are designed to give suitable flying qualities for aircraft evaluated in fixed base and in in-flight simulators.

Where applicable, these requirements are defined in terms of the principal short term mode for aircraft with non-conventional response characteristics. For classical aircraft, read 'short period mode' in the place of the 'short term mode'.

- The CAP or GCAP value shall be set to 0.6 rad/s^2/g;
- The short term mode natural frequency is proportional to the airspeed, as with a classical aircraft, with a suggested value of 1.5 rad/s at the approach airspeed;
- The short term mode damping ratio is set to 0.7;
- The long term mode damping ratio is set to 0.15;
- The maximum initial pitch acceleration/lb control force shall be 0.6 deg/s^2/lb;

- The pitch attitude dropback ($\frac{DB}{q}$)shall be 0.5 seconds at 120 knots, 0.4 seconds at 140 knots and so on until it reaches its minimum value of 0 seconds at 220 knots. Note that this requirement effectively specifies the flight path time delay when the T_{θ_2} value is also considered;
- Where required, the airspeed stability (or static stability) shall give a stick force of 1 lb per 3 knots difference between actual airspeed and trimmed airspeed;
- No aircraft response shall have rate-like characteristics in the flare. In the event of this, the flight control system shall be modified to incorporate a flare law to give attitude-like properties during the flare manoeuvre.

These requirements should give Level 1 flying qualities for the approach and landing flight phase. Note that these requirements are in the middle of the Level 1 flying qualities regions on the appropriate criteria, and should therefore give a well behaved aircraft.

6.4 Aerodynamic Model of the Aircraft Under Investigation

The aircraft model used for this study is a twin-engined 100 seat Generic Regional Aircraft, with a design weight of 90,000 lbs, and a centre of gravity position in the middle of the flight envelope. The engines are mounted under the wing in a similar way to the Airbus A320 (see figure 1.1) or the Boeing 737 (see figure 1.2).

The longitudinal airframe transfer functions used in the flight control system design are given here. DEN is the longitudinal denominator used for all of the transfer functions quoted, and N is the appropriate numerator. Short hand notation is used to write the transfer functions. The appropriate transfer function numerator or denominator may be decoded as follows. For example,

$$\frac{N^{\theta}_{\delta e}}{DEN} = \frac{K^{\theta}_{\delta e}(a)(b)}{[\zeta_s,\omega_s][\zeta_p,\omega_p]} \qquad = \frac{K^{\theta}_{\delta e}(s+a)(s+b)}{[s^2+2\zeta_s\omega_s s+\omega_s^2][s^2+2\zeta_p\omega_p s+\omega_p^2]} \tag{6.11}$$

An airspeed range of 121 to 140 knots for the approach is used. Two flap settings are also used, flap setting 3 is a landing flap setting, but is generally used as an approach setting, since flap setting 4 (full flap) gives more drag, and is therefore used as the final approach flap setting.

140 knots, flap setting 3

$$N^{\gamma_{PS}}_{\delta e} = K^{\gamma_{PS}}_{\delta e}(0.0017)[0.2043, 2.5087] \tag{6.12}$$

$$N_{\delta e}^{\alpha} = K_{\delta e}^{\alpha}(-19.0411)[0.0732, 0.192] \tag{6.13}$$

$$N_{\delta e}^{\theta} = K_{\delta e}^{\theta}(0.584)(0.0646) \tag{6.14}$$

$$DEN = [0.5827, 0.8997][0.0253, 0.1496] \tag{6.15}$$

140 knots, flap setting 4

$$N_{\delta e}^{\gamma_{PS}} = K_{\delta e}^{\gamma_{PS}}(0.0206)[0.2015, 2.5005] \tag{6.16}$$

$$N_{\delta e}^{\alpha} = K_{\delta e}^{\alpha}(-19.044)[0.1066, 0.1915] \tag{6.17}$$

$$N_{\delta e}^{\theta} = K_{\delta e}^{\theta}(0.571)(0.0863) \tag{6.18}$$

$$DEN = [0.5547, 0.9401][0.092, 0.140] \tag{6.19}$$

120 knots, flap setting 4

$$N_{\delta e}^{\gamma_{PS}} = K_{\delta e}^{\gamma_{PS}}(0.0038)[0.2102, 2.1687] \tag{6.20}$$

$$N_{\delta e}^{\alpha} = K_{\delta e}^{\alpha}(-16.2492)[0.0950, 0.2232] \tag{6.21}$$

$$N_{\delta e}^{\theta} = K_{\delta e}^{\theta}(0.4701)(0.1097) \tag{6.22}$$

$$DEN = [0.6083, 0.7465][0.0510, 0.1513] \tag{6.23}$$

200 knots, flap setting 0

$$N_{\delta e}^{\gamma_{PS}} = K_{\delta e}^{\gamma_{PS}}(0.0429)[0.1938, 3.5136] \tag{6.24}$$

$$N_{\delta e}^{\alpha} = K_{\delta e}^{\alpha}(-26.8184)[0.1671, 0.1326] \tag{6.25}$$

$$N_{\delta e}^{\theta} = K_{\delta e}^{\theta}(0.8279)(0.0652) \tag{6.26}$$

$$DEN = [0.5449, 1.3063][0.2851, 0.0797] \tag{6.27}$$

It can be seen that the basic aircraft is operating on the frontside of the drag curve for all of the flight cases considered since the slow zero in the flight path angle transfer function is in the left half of the s-plane. Compared to the required short period mode damping ratio of 0.7, there is reduced short period mode damping of between 0.55 and 0.6. The short period mode natural frequencies are also quite low since they give a CAP value of about 0.18 rad/s^2/g compared to the desired value of 0.6 rad/s^2/g. The phugoid damping is also relatively low for the 120 knot, flap setting 4 case at 0.051. This suggests the basic unaugmented aircraft could be sluggish in the approach and landing flight phase.

In addition, an elevator actuator is included and it is modelled as a first order lag with a 60 m sec time constant. The actuator transfer function is as follows:

$$\frac{NUM_{ACT}}{DEN_{ACT}} = \frac{1}{0.06s + 1} \tag{6.28}$$

6.4.1 Lateral and Directional Stability Modes

The lateral and directional modes of motion are summarised here for completeness.

Roll Mode

Analysis of the aircraft roll mode shows that the inverse roll mode time constant has values between 0.8 seconds at 120 knots, decreasing to 0.4 seconds at 240 knots. Again, this is deemed to be suitable for this type of aircraft.

The proposed MIL-STD [100, 101] standard states that the roll mode time constant for a class III aircraft should be less than 1.3 seconds. For the Generic Regional Aircraft, this requirement is therefore met.

Spiral Mode

Analysis of the aircraft model shows that the spiral mode is always stable, and has an inverse time constant between 0.01 s^{-1} at 120 knots and 0.03 s^{-1} at 200 knots. This is suitable for an aircraft of this type.

Modern fly-by-wire control laws have been programmed so that the pilot is effectively flying an aircraft with zero spiral stability. In other words, the roll inceptor demands roll rate, and the system will hold the roll attitude which is attained when the inceptor is released. Since this aircraft has a stable spiral mode, i.e. it will tend to try to attain a zero roll attitude angle, the unaugmented aircraft may not be suitable for fly-by-wire flight, and a lateral control law may therefore be needed.

Dutch Roll Mode

The Dutch roll damping ratio was found to be approximately equal to 0.06 at 120 knots, increasing to 0.15 at 240 knots. The Dutch roll natural frequency was found to be approximately equal to 1 rad/s at 120 knots, increasing to 1.5 rad/s at 240 knots.

6.5 Command Path Design

The outline structure of the controller is shown in figure 6.6. The structure of the proportional-plus-integral controller has already been described in section 6.1.3. Before the design process for the actual control laws is described, the design of the command path is considered.

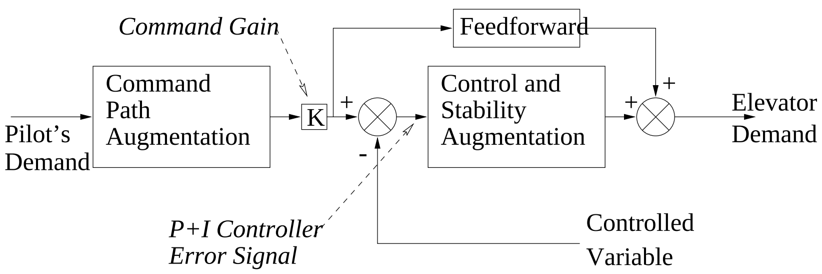


Figure 6.6: Relationship Between the Command Path and the Control and Stability Augmentation for a P+I Controller

The purpose of the command path is to introduce trim to airspeed or trim to angle of attack, to modify the response characteristics for the flare law and to determine the command gain. Although the modifications to the control law characteristics made here are not strictly in the command path since the first three modifications require feedback of one or more of the aircraft states, they do modify the pilot's stick force demand before it is fed through either the feedforward path or used to generate the error signal for the P+I controller. Therefore, these modifications have been termed modifications to the command path. The full command path can be seen in figure 6.7.

6.5.1 The Design of Static Stability

Static stability, or trim to angle of attack characteristics can be generated in a flight control system having a control law with rate-like characteristics by adding a 'front end' onto the control law. This generates an additional control demand in parallel

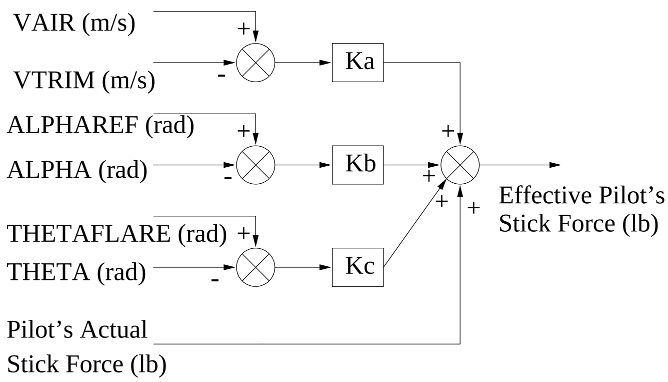


Figure 6.7: The Complete Command Path 'Front End' for a Control Law with Rate-Like Response Characteristics

to the pilot's demand which is proportional to the angle of attack error, or the difference between the trimmed angle of attack and the actual angle of attack.

The angle of attack error term is calculated by taking the difference between the current angle of attack and the reference or trimmed angle of attack. For the purposes of the controller in this set of evaluations, the trimmed airspeed was memorised within the flight control system and modified by movement of the trim button on the wheel. The trim button was therefore disconnected from the horizontal stabiliser. The sense of movement of the trimmer was that of a conventional aircraft, such that pulling down on the thumb-mounted trim switch increases the reference angle of attack, and vice versa. The trim switch changed the reference angle of attack at a rate equivalent to 5 knots per second. The gain Kb determines the control forces per unit angle of attack error and since it is designed to give constant error per unit airspeed error, it is dependent on the current airspeed due to the relationship between airspeed and angle of attack. The control law structure used is shown in figure 6.8.

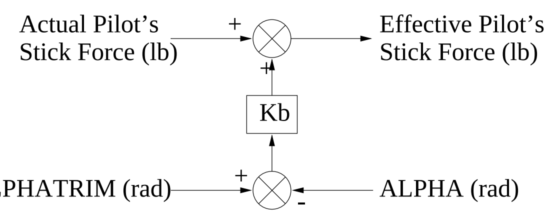


Figure 6.8: Trim to Angle of Attack Command Path Augmentation for a Control Law with Rate-Like Response Characteristics

6.5.2 The Design of Airspeed Stability

Airspeed stability, or trim to airspeed characteristics can also be generated in a similar manner to static stability characteristics. A different 'front end' is required, but the principle of operation is the same as with the trim to angle of attack characteristics.

The sense of movement of the trimmer was again the same as that of a conventional aircraft, i.e. pulling down on the thumb-mounted trim switch lowers the reference airspeed, and vice versa. As before, the trim switch changed the reference airspeed or reference angle of attack at a rate equivalent to 5 knots per second. The control law structure used is shown in figure 6.9. Gain Ka is set to the desired value of stick force per unit airspeed error.

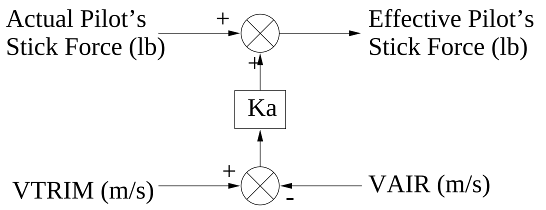


Figure 6.9: Trim to Airspeed Command Path Augmentation for a Control Law with Rate-Like Characteristics

6.5.3 The Design of Monotonic Forces in the Flare

Monotonic forces in the flare can be generated in a flight control system having a control law with rate-like characteristics by adding a 'front end' onto the control law which gives angle-like properties. At a reference height, nominally 50 feet above the runway, the pitch attitude is memorised by the control law. Therefore, in order for the pilot to maintain a pitch attitude greater than the reference value, a constant stick force needs to be held with the stick force being proportional to the difference between the reference pitch attitude and the actual pitch attitude. In order to steadily increase the pitch attitude in the flare to increase the angle of attack and therefore maintain lift as the aircraft decelerates, a monotonic rearwards ramp input is required, giving conventional flare response characteristics.

The control law structure used to do this can be seen in figure 6.10. During normal flight, gain Kc is set to zero. When the flare law is required, Kc is set to the desired value to give the appropriate stick force per unit attitude change, and the pitch attitude at that point of engagement of the flare law is memorised as the reference value THETAFLARE. This structure applies when there is no static stability as the presence of static stability will also generate monotonic forces in the flare.

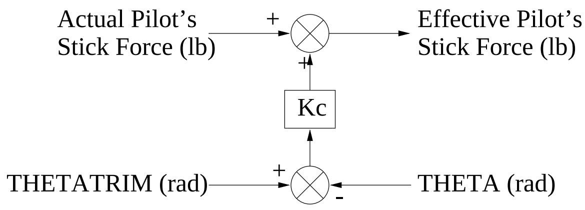


Figure 6.10: Flare Law Command Path Augmentation for a Control Law with Rate-Like Characteristics

6.6 Command and Stability Augmentation Design

6.6.1 The 'Augmented Aircraft' (Angle of Attack) Response Type Control Law Design

This control law was designed with two main purposes in mind. The first was to augment the short period mode frequency to a Level 1 value. It was therefore augmented using angle of attack feedback. The short period damping was also increased to the required value using pitch rate feedback.

Both of the angle of attack and pitch rate feedbacks are scheduled with speed. In addition, the angle of attack feedback gains were scheduled with aircraft flap setting. The phugoid mode characteristics are modified by the feedbacks.

Since this control law was designed to simply augment the characteristics of the short period mode to Level 1 values, no account was taken of dropback explicitly in the design process, though a lead-lag filter or feeding back pitch attitude could address this if changes were required to give good flying qualities.

Controller Structure

The controller structure can be seen in figure 6.11. It can be seen that three command gains are used, and are listed as follows:

1. K1 - Angle of attack to elevator gain. This gain was used to increase the short period mode frequency, and was scheduled with respect to speed and aircraft flap setting. The short period mode natural frequency was set at 1.5 rad/s at 120 knots, increasing by 0.25 rad/s for each subsequent 20 knots;
2. K2 - Pitch rate to elevator gain. This gain was used to increase the short period mode damping, and it was scheduled with respect to airspeed. The

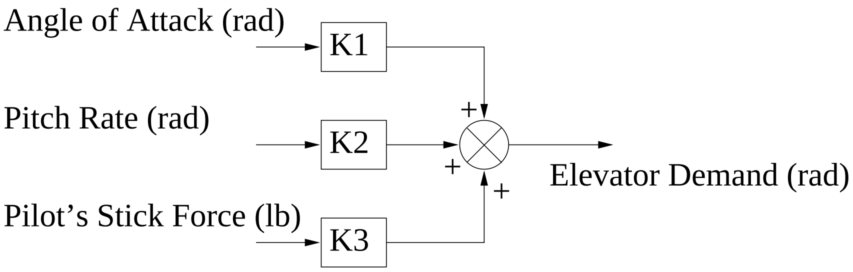


Figure 6.11: Angle of attack law conceptual diagram

short period mode damping ratio was set at 0.7 for all of the flap settings considered;

3. K3 - Pilot's stick force to elevator gain. Due to the nature of the feel characteristics, the feel system required gain scheduling to allow for airspeed variations. This was carried out in the classical form by specifying this gain as a function of airspeed.

Design Process

The control law design process is quite simple for this control law. It has been deliberately designed with simplicity in mind so that it could possibly be regarded as the cheapest option if augmentation is required for an aircraft. The design process is as follows, and must be repeated for each individual design case:

1. Augment the short period mode natural frequency with angle of attack feedback;

2. Augment the short period damping with pitch rate feedback;

3. Select command gain.

6.6.2 Pitch Rate Command with Attitude Hold Control Law Design

This section describes the design of the pitch rate command control law.

Controller Structure

The controller structure can be seen in figure 6.12. It can be seen that eight command gains are used, and are listed as follows. This controller structure is used for all of the generic pitch rate laws, and therefore some of the gains may be set to zero.

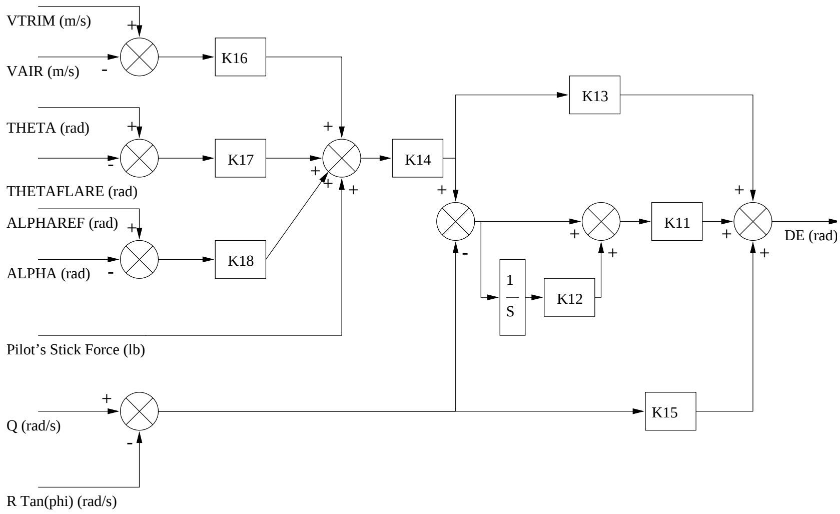


Figure 6.12: Generic Pitch Rate Control Law Conceptual Diagram

1. K11 - Overall controller to elevator gain. Increasing K11 has the effect of increasing the natural frequency of the short term mode plus increasing the damping ratio of the long term mode;

2. K12 - Integrator to Proportional controller gain. This gain was used to increase the short term mode natural frequency and decrease the short term mode damping;

3. K13 - Feedforward gain. This gain is used to modify the dropback characteristics of the initial response. Increasing the dropback has the effect of increasing the 'quickness' of the initial pitch rate response. It also controls the location of the controller zero which is found in all of the elevator transfer functions for a given value of K12. This enables the flight path response to be approximated to K/s in the crossover region, which corresponds to a zero placed around the same location as the $1/T_{\theta_2}$ location;

   The location of the zero has the effect of altering the dropback for all other gains fixed. Increasing the value of the K13 gain increases the dropback as the zero introduced by the controller decreases in frequency, although whether these two are connected is unknown. Certainly, increasing the initial pitch rate response increases the dropback, and this initial response is tied to the value of the feedforward;

4. K14 - Command gain. This is used to control the magnitude of the response to the pilot's input. Due to the nature of the feel characteristics, the feel system required gain scheduling to allow for speed variations. This was carried out in the classical form by modifying the basic stick force gradient and the actual command gain itself;

5. K15 - Damping component. This gain is used to control the short term mode damping ratio. Note that this gain is redundant, but has been included since it simplifies the design process;
6. K16 - Airspeed error to stick force gain. This gain generates a stick force dependent on the airspeed error calculated from the value referenced from the trim wheel, and the current airspeed. This gain is only set to a non-zero value when airspeed stability is required;
7. K17 - Flare law gain. This gain is used to give attitude like characteristics in the flare, and is only set to a non-zero value when the flare law is active;
8. K18 - Angle of attack error to stick force gain. This gain is used to give angle of attack stability. It generates a stick force depending on the size of the angle of attack error. The size of this gain was determined from the required airspeed error to stick characteristic. This value was used since a higher value gives excessive dropback, which it is not possible to correct for using the feedforward gain or a prefilter.

The four gains K11, K12, K13 and K15 may be replaced with three gains, since it is possible to demonstrate that K15 is redundant. However, it has been included in the design process since it makes the design process easier if the K12 gain is fixed at some nominal value, and then the other gains are designed around that fixed value. If the gain K15 is set to zero, then the other gains will have to be modified to account for this, but the modifications are easily determined.

Design Process

The control law design process is relatively straightforward for this control law. The process is as follows, and must be repeated for each individual design case. If speed stability using speed feedback is required then the speed error to stick force, gain K16, must be set. If speed stability using angle of attack feedback is required, then the required angle of attack to stick force gain must be set using gain K18. If angle of attack speed stability is required, then gain K18 must be set during the design process for gains K11-15 since it will have a significant effect on the closed loop dynamics. The process is:

1. Decide on the required short term mode characteristics;
2. Decide on the value for the gain K12;
3. Augment the short term mode natural frequency with the gain K11;
4. Augment the short term mode damping ratio with pitch rate feedback using gain K15;

5. Repeat the previous 2 steps until the characteristics are suitable;
6. Select the required dropback using gain K13;
7. Select command gain using K14;
8. Iterate if necessary.

If a flare law is required then the reference height and the value for the gain K17 must be decided. For all other cases, the gain K17 is set to zero. The flare law is only required for a pure pitch rate demand system.

It was found that gain schedules were required for the majority of the control gains for the pure pitch rate law, with the exception of K12, which was deliberately kept fixed in order to facilitate the design process. K11 and K13 are scheduled with speed and aircraft flap setting, and K14 and K15 are scheduled with speed alone. K16 is used to give speed stability, and is set to zero for this control law. K17 is used for the flare law, and has a constant value during the period when the flare law is armed.

Flare Law

Due to the nature of this response type, it has non-monotonic stick forces in the flare. Field showed that this is unsuitable for the landing task [4]. In addition, current aircraft which would exhibit pitch rate type responses use a modified law to enable the pilot to use monotonic forces in the flare.

Therefore a law was designed which memorised a reference pitch attitude at a certain height (initially set to 40 feet), and then summed the difference between this pitch attitude value and the current pitch attitude with the pilot's demand. This produced a control system which required the pilot to hold a certain pitch force in the flare which increased as the required attitude increased. Therefore monotonic forces increased. The K17 gain, which is used to do this, is set to 60 lbs/rad, though 100 lbs/rad was later found to be more suitable.

6.6.3 Pitch Rate Command with Trim to Airspeed Control Law Design

This law is essentially identical to the pitch rate law previously described, except that speed error feedback is employed to artificially induce speed stability. This type of law exists in similar forms (some combat aircraft employ angle of attack error feedback to generate a positive static margin).

Due to the speed feedback, no specific flare law is needed. If the aircraft is trimmed at an approach speed of, say, 121 knots, the pilot will have to maintain rearwards stick pressure for the aircraft to stabilise at a lower speed for a constant pitch attitude. Therefore the fact that airspeed is fed back to the demand generates a conventional flare law, with the required longitudinal stick input required during the flare being something like a monotonic ramp input.

This law is designed in the same way as the pure pitch rate law. The final stage in the design process however is to decide on the speed feedback gain. No problems were experienced during the design process for the derivation of the speed feedback gain with the system becoming unstable. A fuller explanation of the effects of feeding back airspeed can be found in section 6.5. In addition, no flare law is required for the reasons just mentioned, and therefore the K17 gain was set to zero.

6.6.4 Pitch Rate Command with Trim to Angle of Attack Control Law Design

This law is essentially identical to the pitch rate law previously described, except that angle of attack error feedback is employed to artificially induce speed stability. This type of law is also untested, although it exists in similar forms (some combat aircraft employ angle of attack error feedback to generate a positive static margin).

Due to the angle of attack feedback, no specific flare law is needed. If the aircraft is trimmed at an approach speed of, say, 121 knots, the pilot will have to hold the stick back for the aircraft to stabilise at a lower speed for a constant pitch attitude. Therefore the fact that angle of attack is fed back to the demand generates a conventional flare law, with the required longitudinal stick input required during the flare being something like a monotonic ramp input.

This law is designed in the same way as the pure pitch rate law. However, the first stage in the design process is to decide on the angle of attack to stick force gain. In addition, no flare law is required for the reasons just mentioned, and therefore the K17 gain was set to zero. This control law has gain schedules which are scheduled with speed.

6.6.5 C* Command Control Law Design

This section describes the design process for the C* command control law.

Design Process

The design process used for the C* command law at low to medium speeds is essentially identical to the process for the pitch rate control law. It can be characterised by the following steps.

1. Select the required value for the ratio of normal acceleration to pitch rate for the derivation of the 'C*' value;

2. Decide on the initial value of the Integral to Proportional ratio for the integrator component of the controller, gain K22;

3. Obtain the desired short term mode frequency and damping from adjusting the two primary controller gains, gains K21 and K22. In this case it is necessary to obtain the desired short term mode characteristics by modifying these two gains since the pure pitch rate gain, K15, which was included with the pitch rate controller is not present;

4. Set the pitch attitude dropback at the required value using the feedforward gain, K23;

5. Set the command gain using the required value for the initial pitch acceleration, K24.

The controller structure can be seen in figure 6.13. It can be seen that eight command gains are used and are listed as follows.

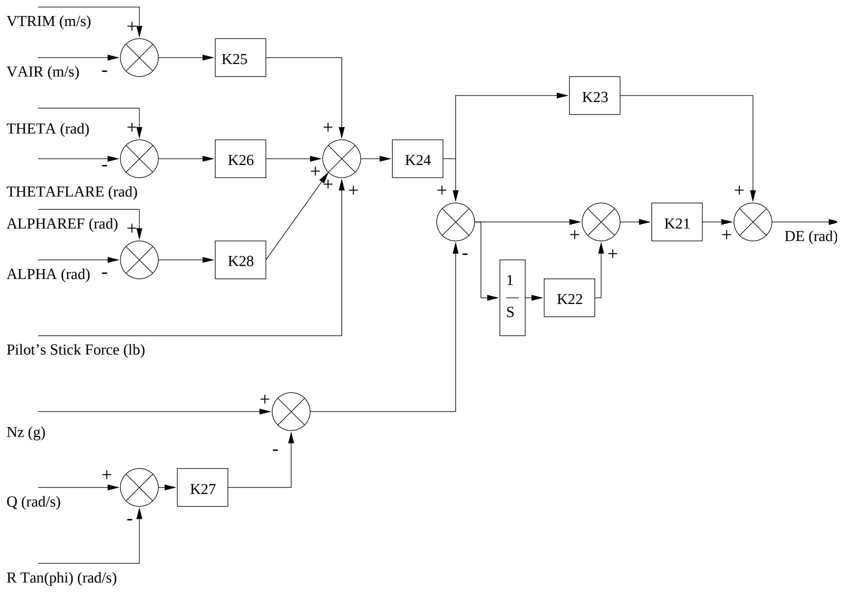


Figure 6.13: Generic C* Control Law Conceptual Diagram

1. K21 - Overall controller gain. This gain increases the natural frequency of the short term mode. There is also a marked effect on the long term response;

2. K22 - Integrator to proportional controller gain. This gain increases the frequency and reduces the damping ratio of the short term mode;

3. K23 - Feedforward gain. This gain is used to modify the dropback characteristics of the control law;

4. K24 - Command gain. This gain is used to determine the magnitude of the aircraft's response to a pilot's inputs. This gain requires scheduling with airspeed;

5. K25 - Airspeed error to stick force gain. This gain generates a stick force dependent on the airspeed error calculated from the value referenced from the trim wheel, and the current airspeed. This gain is only set to a non-zero value when airspeed stability is required;

6. K26 - Flare law gain. This gain is used to give attitude like characteristics in the flare, and is only set to a non-zero value when the flare law is active;

7. K27 - C* blend gain. Since C* is a blend of pitch rate and normal acceleration, the blend must be determined. For the purposes of this law, the classical C* value of 12.4 g/rad/s was used;

8. K28 - Angle of attack error to stick force gain. This gain is used to give angle of attack stability. It generates a stick force depending on the size of the angle of attack error. The size of this gain was determined from the required airspeed error to stick characteristic, and a value of 6 knots per pound stick force was initially selected when angle of attack stability was required. This value was used since a higher value gives excessive dropback, which it is not possible to correct for using the feedforward gain or a prefilter.

It was found that gain schedules were required for most of the control gains. K22 is scheduled with airspeed and aircraft flap setting, and K21 and K23 are scheduled with airspeed alone. K25 is used to give airspeed stability, and is set to zero for this control law. K26 is used for the flare law, and has a constant value during the period when the flare law is armed. The value of the C* blend gain, K27, is set to 12.4 seconds, which is the value for classical C*. This ratio can be modified if necessary.

Flare Law

Due to the pitch rate like response characteristics of this law at low speed, a flare law was introduced in the same way as the flare law for the pitch rate command system.

6.6.6 C* Command with Trim to Airspeed Control Law Design

This law is essentially identical to the C* law previously described, except that speed error feedback is employed to artificially induce speed stability. This type of law exists in similar forms (some combat aircraft employ angle of attack error feedback to generate a positive static margin). Again, as with the pitch rate with speed feedback law, no specific flare law is needed.

This law is designed in the same way as the pure C* law. The final stage in the design process however is to decide on the speed feedback gain. No problems were experienced during the design process for the derivation of the speed feedback gain with the system becoming unstable. The same can not be said for the normal acceleration control law. A fuller explanation of the effects of feeding back speed can be found in section 6.5.

6.6.7 C* Command with Trim To Angle of Attack Control Law Design

This law is essentially identical to the C* law previously described, except that angle of attack error feedback is employed to artificially induce speed stability. This type of law exists in similar forms (some combat aircraft employ angle of attack error feedback to generate a positive static margin). Again, as with the pitch rate with angle of attack feedback law, no specific flare law is needed. Again, this law is designed in the same way as the pure C* law. However, the first stage in the design process is to decide on the angle of attack to stick force gain.

6.6.8 Normal Acceleration Command with Flight Path Angle Hold Control Law Design

This section describes the design process for the normal acceleration command control law.

Design Process

The design process comprises the following steps.

1. If speed stability using speed feedback is required then the speed error to stick force, gain K36, must be set. If speed stability using angle of attack feedback is required, then the required angle of attack to stick force gain must be set, gain K38. If angle of attack speed stability is required, then gain K38 must be

set during the design process for gains K31 to K35 and K39 since it will have a significant effect on the closed loop dynamics;

2. Select the desired short and long term modal properties;

3. Decide on the integral to proportional ratio for the integrator component of the controller;

4. Select the appropriate overall controller gain to give the required short term mode frequency;

5. Obtain the desired short term mode and long term mode damping from adjusting the gains K33 and K39. Increasing the value of gain K33 will increase the short term mode damping ratio only. Increasing the value of K39 increases the value of both the short and long term mode damping ratios. This is due to the fact that K39 gives both pitch rate feedback and integral pitch rate feedback, which is similar to pitch attitude feedback, and pitch attitude feedback traditionally increases the damping of the long term mode. This gain is required since pitch rate is the only effective way of increasing the short term mode damping;

6. Set the pitch attitude dropback at the required value using the feedforward gain;

7. Set the command gain using the required value for the initial pitch acceleration.

The controller structure can be seen in figure 6.14. It can be seen that nine command gains are used, and are listed as follows.

1. K31 - Overall controller gain. This gain increases the natural frequency of the short term mode. There is also a marked effect on the long term response;

2. K32 - Integrator to proportional controller gain. This gain increases the frequency and reduces the damping ratio of the short term mode;

3. K33 - Pitch rate to elevator gain. This gain is used to provide short term mode damping;

4. K34 - Feedforward gain. This gain is used to modify the dropback characteristics of the control law;

5. K35 - Command gain. This gain is used to determine the magnitude of the aircraft's response to a pilots inputs;

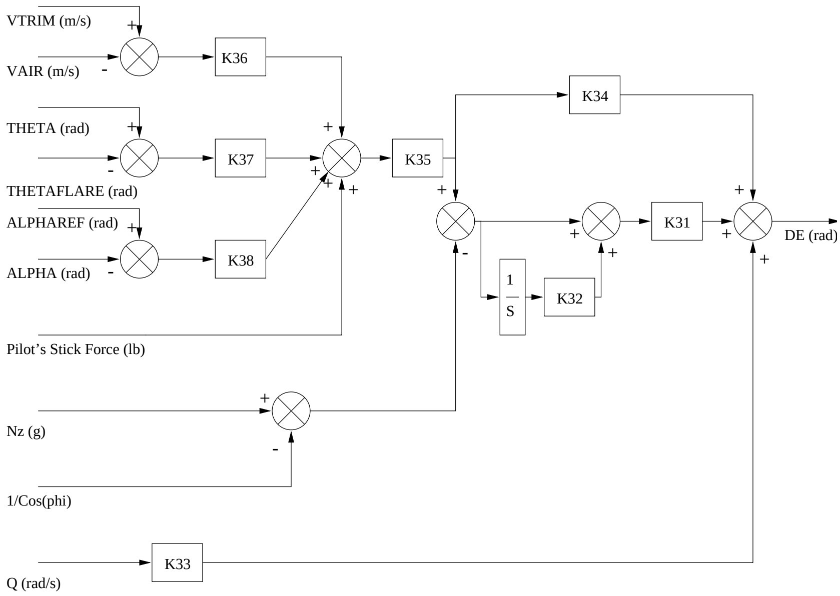


Figure 6.14: Generic Normal Acceleration Control Law Conceptual Diagram

6. K36 - Airspeed error to stick force gain. This gain generates a stick force dependent on the airspeed error calculated from the value referenced from the trim wheel, and the current airspeed. This gain is only set to a non-zero value when airspeed stability is required;

7. K37 - Flare law gain. This gain is used to give attitude like characteristics in the flare, and is only set to a non-zero value when the flare law is active;

8. K38 - Angle of attack error to stick force gain. This gain is used to give angle of attack stability. It generates a stick force depending on the size of the angle of attack error. The size of this gain was determined from the required airspeed error to stick characteristic, and a value of 6 knots per pound stick force was initially selected. This value was used since a higher value gives excessive dropback, which it is not possible to correct for using the feedforward gain or a prefilter;

9. K39 - Pitch rate to controller gain. This gain was used to assist with the damping of the short and long term modes.

It was found that gain schedules were required for most of the control gains. Gains K31, K32, K33, K34 and K35 all required speed schedules. Of the other gains, K36 is used to give speed stability, and is set to zero for this control law. K37 is used for the flare law, and has a constant value during the period when the flare law is armed.

Flare Law

Due to the rate like response characteristics of this law, a flare law was introduced in the same way as the flare law for the pitch rate command system.

6.6.9 Normal Acceleration Command with Trim to Airspeed Control Law Design

This law is designed in the same way as the pure normal acceleration law. The final stage in the design process however is to decide on the speed feedback gain. The calculation of this gain was found to be a problem at high speed, the law behaves in a normal acceleration like manner, and it was found that the maximum permitted value of the speed error feedback gain was drastically limited so that the control forces required to hold a specified speed error were extremely light. This questions the usefulness of having the speed feedback present since it is there to 'remind' the pilot when he is flying at an off-trim speed through tactile feedback of stick forces. A fuller explanation of the effects of feeding back speed can be found in section 6.5. In addition, no flare law is required and the K37 gain was set to zero.

6.6.10 Normal Acceleration Command with Trim to Angle of Attack Control Law Design

In the same way that a pitch rate with angle of attack feedback is an extension to a pure pitch rate law, normal acceleration with angle of attack feedback is an extension to a pure normal acceleration law. Speed stability is introduced by feeding back an angle of attack error, or the difference between the current angle of attack and a reference value set by the pilot using the trimmer, in parallel with the pilot's demands. Therefore for the pilot to maintain an 'off-reference' value, a specified stick force needs to be held. No aircraft explicitly uses a normal acceleration with trim to angle of attack control law.

This law is designed in a similar way as the pure normal acceleration law. However, the initial angle of attack gain must be decided beforehand since angle of attack feedback has a significant effect on the short term dynamics. The required angle of attack gain can be decided in several ways. The overall response characteristics can be examined, or the characteristics of the long term mode induced, or the required stick force per speed error can be used to enable this gain to be calculated. None of the problems experienced with speed feedback at higher speeds were experienced. This is due to the fact that there are no right half plane zeros in the angle of attack to elevator transfer function, and therefore the angle of attack gain can be increased without fear of the left half plane poles close to the origin migrating into the right half plane.

In addition, no flare law is and gain K37 was set to zero.

6.6.11 The Design of the Fly-by-wire Lateral Control Law

The fly-by-wire lateral control law is typical for a fly-by-wire aircraft and had already been designed for this aircraft. It is based on the principle that zero spiral stability is desirable up to a specified angle of bank, in this case 35 degrees, so that the pilot does not have to work to maintain a specified turn rate. However, above 35 degrees, positive spiral stability is used since it prevents the pilot from achieving excessive angles of bank as he receives tactile feedback that the angle of bank is becoming excessively large.

The control gains for this law are gain scheduled with a ‘q-pot’ to give a realistic feel system. The lateral laws used have been used previously, and are deemed to be appropriate for this aircraft and task.

6.6.12 The Design of the Yaw Damper and Turn Coordination

The aircraft in question has quite a low Dutch roll damping ratio, and therefore the yaw damper / turn coordinator is a vital piece of equipment. A yaw damper was already modelled and it consists of the following feedbacks to the rudder:

1. Lateral acceleration. This provides the turn coordination function by minimising lateral acceleration during the turn;
2. Washed out yaw rate (or a gain with a high pass filter). This is used to increase the Dutch roll damping. The high pass filter removes the steady state component which exists when the aircraft is in a turn;
3. Washed out roll attitude. This is used to improve the lateral acceleration characteristics during turn entry and exit.

Turn coordination was also implemented, despite the fact that the lateral handling qualities are not being specifically evaluated as it is important that the flight control laws are as representative as possible of the command concepts used so that they give each concept a fair evaluation. In the case of pitch rate command laws, if the required body pitch rate to coordinate the turn was derived so that the pilot did not have to perform the coordinating action to maintain height during the turn himself. This was tested on the Cranfield engineering flight simulator, and the results were successful. For the normal acceleration control laws, the turn coordination was effected by calculating the load factor required to coordinate the turn at a specific angle of bank, and then feeding this into the longitudinal control laws. For the C* control laws, the coordination was performed by a mixture of both methods.

Fly-by-wire civil aircraft which have turn coordination tend to only coordinate turns up to certain angles of bank. This is so that the pilot is discouraged from exceeding specific attitudes since he would have to hold significant control forces to maintain these attitudes. These features were not explicitally modelled since the pilots were not achieving the high bank attitudes (say above 45 degrees) to require these systems. However, the inclusion of such a system would be a reasonably straightforward task.

6.7 The Design of the Autothrottle

The autothrottle was designed as a simple airspeed hold system. It maintained a pre-selected airspeed during the approach until the flare, when it demanded idle power from the engines at a specified height, nominally 40 feet. The description of the autothrottle is included in reference [58].

7 Evaluation of a Reconfiguration and ILS Approach Task

The flying qualities evaluation described within this Chapter considers a reconfiguration, approach and landing task for a generic regional aircraft. Several different control laws were assessed against this task, and the results are documented here.

7.1 Engineering Flight Simulator Description

The Engineering Simulator used for the primary evaluations was designed and manufactured at British Aerospace Hatfield, but is now located at British Aerospace Regional Aircraft, Woodford. It is used primarily for engineering development work, some flight crew training and some certification activity.

The simulator is a fixed base device with a simulation cab which represents a British Aerospace 146 / Avro RJ cockpit. The visual system consists of two outside views per seat, one centre window, and one mounted to the outside of the centre display. This gives a good forward view plus an oblique side view, which was not required for this evaluation series. The outside view depicted is a night visual scene, with 8 levels of grey. The navigation fit is a phase II Avro RJ fit, with an EFIS Primary Flight Display, Navigation Displays and servo altimeters on both sides. Height callouts for the ILS approach tasks are made at 500, 100, 50, 40, 30, 20 and 10 feet, as well as a glideslope callout at one mile.

Simulations are run on a dedicated DEC VAX4000 computer using an update rate of 50 Hz. Intervention during simulation is possible through a computer terminal mounted in the simulation cab. For the purposes of the evaluation, the aircraft was flown from the left hand seat by the evaluation pilot with the test administrator sitting in the right hand seat. No flying was performed from the right hand seat.

Inceptor and Feel System Description

The cockpit consists of a centre wheel control inceptor, with a fully programmable active feel system, which runs at 500 Hz. A fully programmable active sidestick is also fitted but was not used for these evaluations. The system is able to simulate end-stops, constant loads, damping, friction and spring forces.

The feel system used for the evaluations had the following characteristics. The elevator had a spring force of 12 lb/in (including the component from the q-pot with a breakout of 0.5 lb and a damping of 0.5 lb/in/sec. The aileron feel system comprised a spring force of 4 lb/deg at approach airspeeds including the contribution from the q-pot and 0.2 lb friction and 0.03 lb/deg/sec damping. The rudder feel system comprised a spring of 42 lb/in with a breakout of 15 lb.

The positions for the elevator and aileron are measured at the centre of the top of the control wheel yokes, and the rudder characteristics are measured at one of the pedals.

Actuator Dynamics and Flight Control System Hardware Description

Elevator actuators were modelled as simple first order lags with a time constant of 60 msec. No other actuators were modelled. These actuators were assumed to be identical for all aircraft evaluated. The flight control system was assumed to be perfect with no additional delays or lags other than those associated with the simulation process, and no allowance for failures was made. The maximum lag due to the simulation process was 40 msec, with an average lag of around 20 msec.

A proposed flight control system hardware design for this type of aircraft may be found in reference [5].

Ground Effect Model Description

The ground effect model used was developed for the baseline aircraft. It consists of increments to the pitching moment and lift force based on a height schedule. The exact characteristics are confidential but they have been validated by one of the project development pilots.

Engine Model Description

Four engine levers are fitted, but only the inner two are used since the aircraft under consideration only has two engines. Full engine displays are fitted, with the primary engine display being engine fan-speed (N1), to which power settings were referenced. The engine itself had a simulated Full Authority Digital Engine Control (FADEC) system which is a N1 demand system. The engine N1 demand was generated from the appropriate power lever position.

Atmospheric Disturbances Description

Atmospheric disturbances were available in the model. Turbulence was not used for these evaluations, but a decreasing headwind was used for the evaluations described within Chapter 8.

Flap Configuration Description

The aircraft has a total of five flap positions. These are labelled 0 to 4. Positions 3 and 4 are generally used for approach and landing. Position 2 is generally used for take-off. Only positions 3 and 4 were used for these evaluations.

7.2 Flying Qualities Experiment Design

This section describes the evaluation procedure used for the flying qualities experiment described within this Chapter. DeWitt [102] states that the tests must meet four definite criteria.

1. Instantaneously measurable performance;
2. Operational relevance;
3. Repeatability;
4. Sufficient gain for the pilot to evaluate all axes.

Of these requirements, the last is the least important due to the primary investigation being restricted to the longitudinal axis, minimising disturbances in the lateral and directional axes. These evaluations have been used to examine control law performance in the following areas.

1. Changes in airspeed;
2. Flap deployment / reconfiguration;
3. ILS tracking performance;
4. The effects of an autothrottle;
5. The effect of transitioning to the baseline aircraft in the event of flight control system failures.

The evaluation task used comprised the following segments, and the flare component may be seen in figure 7.1.

1. The evaluation was commenced 8 miles from touchdown at 140 knots (V_{REF} + $\approx$ 20 knots) flap configuration 3 and at a height of 1250 feet above the aerodrome airfield. The aircraft was flown for 2 miles in this condition to allow the evaluation pilot to stabilise the aircraft. The evaluation was started with the aircraft in trim and with the required power set.
2. Flap deployment to the landing configuration (configuration 4) was performed at 6 miles. The pilot was required to maintain airspeed and height, which needed an increase in power and possibly a pitch input. The flap lever was moved by the test administrator.

3. Intercept and maintain the ILS glideslope at approximately 4 miles still at 140 knots. This required a power reduction and possibly a pitch input.

4. When fully established on the glideslope, slow down to maintain the final approach airspeed of 121 knots (V_{REF} + 5 knots), again requiring a power reduction and possibly a pitch input.

5. Correct for any vertical offset at 1 mile. A glideslope call was made by the Ground Proximity Warning System (GPWS) which was the cue for the pilot to make any necessary correction to land in the touchdown zone. Since the ILS glideslope was displaced vertically upwards, this requires quite a large power reduction and an aggressive pitch input.

6. Flare and land within the marked touchdown zone, again requiring a power reduction (to idle power) and a pitch input.

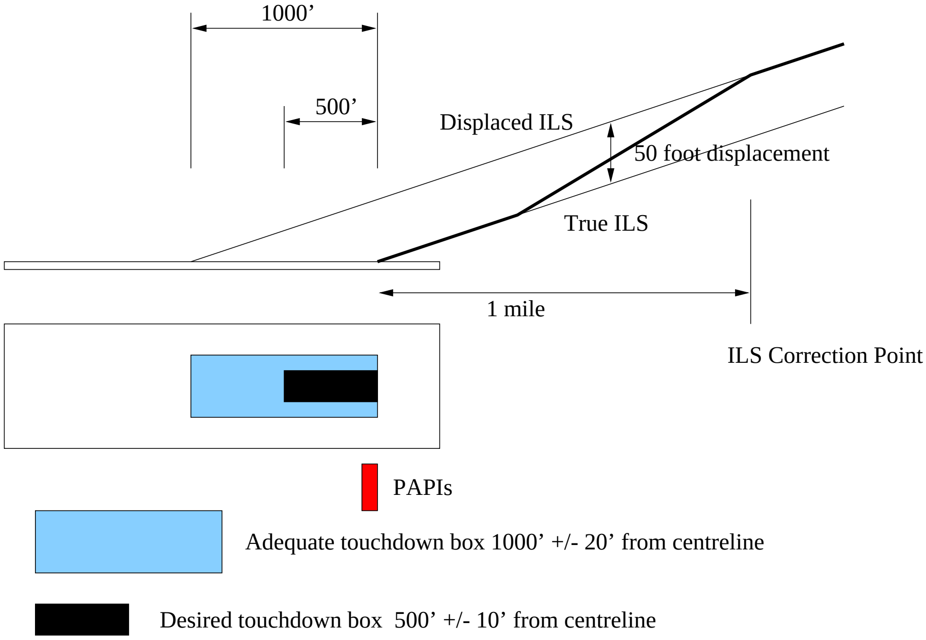


Figure 7.1: Offset ILS Description

This evaluation segment was repeated a number of times. The evaluation pilot was initially given 2 or 3 approaches with the unaugmented (baseline) aircraft to familiarise himself with the procedure. He then carried out either 2 or 3 approaches with the control law under consideration, but without the autothrottle active. After these approaches, the pilot and test administrator completed the first portion of the pilot comment card. The pilot then flew a further 1 or 2 approaches with the same control law and the autothrottle engaged, and then the pilot and test administrator completed the second portion of the pilot comment card. Finally, the pilot had an optional approach with the baseline aircraft before completing the final part of the comment card (which concerned the evaluation pilot's opinion concerning the ability to transition from the appropriate control law to the baseline aircraft in the case of failure).

7.3 Control Law Design Criteria

The design requirements described in section 6.3 were used to design the control laws for this evaluation task.

7.4 Control Law Analysis Against the Criteria

The control law characteristics can be seen in the following set of tables 7.1 to 7.8 and in figures 7.2 to 7.5. However, there is some variation in the design characteristics which could be improved with further iteration. The following control laws were used:

Law Reference	Description.
Base	Unaugmented Aircraft.
1	Augmented Angle of Attack.
2	Pitch Rate.
3	Pitch Rate with trim to Airspeed.
4	C*.
5	C* with trim to Airspeed.
6	Normal Acceleration.
7	Normal Acceleration with trim to Airspeed.
8	Pitch Rate with trim to Angle of Attack.
9	C* with trim to Angle of Attack.
10	Normal Acceleration with trim to Angle of Attack.

The Bandwidth Criterion

The values for the pitch attitude and flight path bandwidths can be seen in table 7.1 and figures 7.2 and 7.3. It can be seen that all of the augmented aircraft have Level 1 bandwidth characteristics, but the unaugmented aircraft is borderline Level 2 / 3.

Law Number	ω_{BW_θ} (rad/s)	$\omega_{BW_{\gamma P}}$ (rad/s)	Phase rate (deg/Hz)	Phase Delay (s)	-180 deg phase Frequency (Hz)
Base	0.7836	0.4720	65.56	0.0910	0.3920
1	2.0402	1.0633	65.06	0.0900	0.7830
2	1.9843	0.9639	63.75	0.0890	0.7510
3	1.9761	0.8918	63.65	0.0880	0.7500
4	2.0637	1.0029	55.27	0.0770	0.8150
5	2.0595	1.0082	55.22	0.0770	0.8150
6	2.1211	0.8120	44.30	0.0620	0.9750
7	2.1328	0.8873	44.31	0.0620	0.9750
8	1.4023	0.6522	96.00	0.1330	0.5340
9	2.2854	1.2436	59.55	0.0830	0.8360
10	1.5585	0.8709	59.79	0.0830	0.7180

Table 7.1: Bandwidth and Phase Delays for the Landing Flight Case (120 knots, Flap 4)

The Phase Delay Criterion

The phase delay characteristics can be seen on table 7.1 and figure 7.4. It can be seen that all of the aircraft should not be PIO prone for the short term response characteristics.

The Neal-Smith Criterion

The Neal-Smith characteristics can be seen in tables 7.2 to 7.4, and on figure 7.5 for the landing flight case. It can be seen that all of the resonance values are low, and all of the pilot compensation values are within Level 1 limits except for the unaugmented aircraft, which requires excessive pilot compensation.

CAP and GCAP Criteria

From table 7.5, it can be seen that all of the augmented control laws have approximately similar values of GCAP, although the CAP values do not correspond as well for some of the different control laws. This demonstrates why CAP in its current form, is not suitable for use with augmented non-conventional response types, especially normal acceleration demand systems since the results from different response types are not directly comparable.

Gibson's Dropback Criterion

Gibson's dropback results may be seen in figure 7.6 and table 7.6. Although the law 2 to law 10 aircraft were designed to nominally the same dropback values, there

	140 knots, flap 3, with actuator		140 knots, flap 3, no actuator	
	NS compensation (deg)	NS resonance	NS compensation (deg)	NS resonance
Base	81.00 lead	-3 dB	70.19 lead	-3 dB
1	15.24 lag	-2.95 dB	16.06 lag	-3 dB
2	9.087 lag	-3 dB	9.50 lag	-3 dB
3	8.723 lag	-3 dB	9.106 lag	-3 dB
4	13.71 lag	-2.993 dB	13.8 lag	-3 dB
5	13.55 lag	-3 dB	13.71 lag	-3 dB
6	3.617 lag	-2.314 dB	3.584 lag	-2.478 dB
7	3.887 lag	-2.26 dB	3.847 lag	-2.425 dB
8	13.56 lead	-2.992 dB	13.99 lead	-3 dB
9	26.65 lag	-3 dB	26.46 lag	-3 dB
10	12.97 lead	-3 dB	12.9 lead	-3 dB

Table 7.2: Neal-Smith Compensation and Resonance Values for 140 knots Flap 3

	140 knots, flap 4, with actuator		140 knots, flap 4, no actuator	
	NS compensation (deg)	NS resonance	NS compensation (deg)	NS resonance
Base	72.32 lead	-2.943 dB	62.91 lead	-3 dB
1	15.37 lag	-2.942	16.23 lag	-3 dB
2	10.43 lag	-2.994	10.9 lag	-3 dB
3	10.01 lag	-3 dB	10.49 lag	-3 dB
4	13.77 lag	-3 dB	14 lag	-3 dB
5	13.57 lag	-3 dB	13.82 lag	-3 dB
6	3.931 lag	-2.388 dB	3.955 lag	-2.545 dB
7	4.208 lag	-2.333 dB	4.226 lag	-2.491 dB
8	13.19 lead	-2.993 dB	13.44 lead	-3 dB
9	26.59 lag	-3 dB	26.55 lag	-3 dB
10	12.2 lead	-3 dB	11.88 lead	-3 dB

Table 7.3: Neal-Smith Compensation and Resonance Values for 140 knots Flap 4

	120 knots, flap 4, with actuator		120 knots, flap 4, no actuator	
	NS compensation (deg)	NS resonance	NS compensation (deg)	NS resonance
Base	114.4 lead	-2.996 dB	98.85 lead	-2.997 dB
1	7.818 lag	-2.341 dB	8.19 lag	-2.69 dB
2	4.163 lag	-2.48 dB	3.972 lag	-2.763 dB
3	3.27 lag	-2.612 dB	3.177 lag	-2.865 dB
4	7.1 lag	-2.388 dB	6.742 lag	-2.635 dB
5	6.653 lag	-2.466 dB	6.368 lag	-2.696 dB
6	4.791 lead	-2.575 dB	4.983 lead	-2.805 dB
7	4.158 lead	-2.468 dB	4.263 lead	-2.685 dB
8	29.58 lead	-3 dB	29.96 lead	-3 dB
9	18.6 lag	-2.476 dB	18.13 lag	-2.715 dB
10	4.62 lead	-.9274 dB	5.684 lead	-1.341 dB

Table 7.4: Neal-Smith Compensation and Resonance Values for 120 knots Flap 4

	140 knots, flap 3		140 knots, flap 4		120 knots, flap 4	
	CAP	GCAP	CAP	GCAP	CAP	GCAP
Base	0.188	0.190	0.210	0.208	0.188	0.187
1	0.714	0.672	0.728	0.668	0.741	0.689
2	0.713	0.550	0.733	0.566	0.760	0.593
3	0.711	0.563	0.733	0.578	0.756	0.609
4	0.720	0.626	0.745	0.626	0.750	0.641
5	0.719	0.632	0.744	0.632	0.749	0.649
6	0.190	0.569	0.197	0.569	0.195	0.619
7	0.191	0.565	0.198	0.567	0.197	0.616
8	0.682	0.295	0.731	0.294	0.736	0.286
9	0.943	0.860	0.973	0.859	0.951	0.843
10	0.339	0.378	0.360	0.376	0.520	0.464

Table 7.5: CAP and GCAP Values for the Landing Flight Case, 120 knots, flap 4

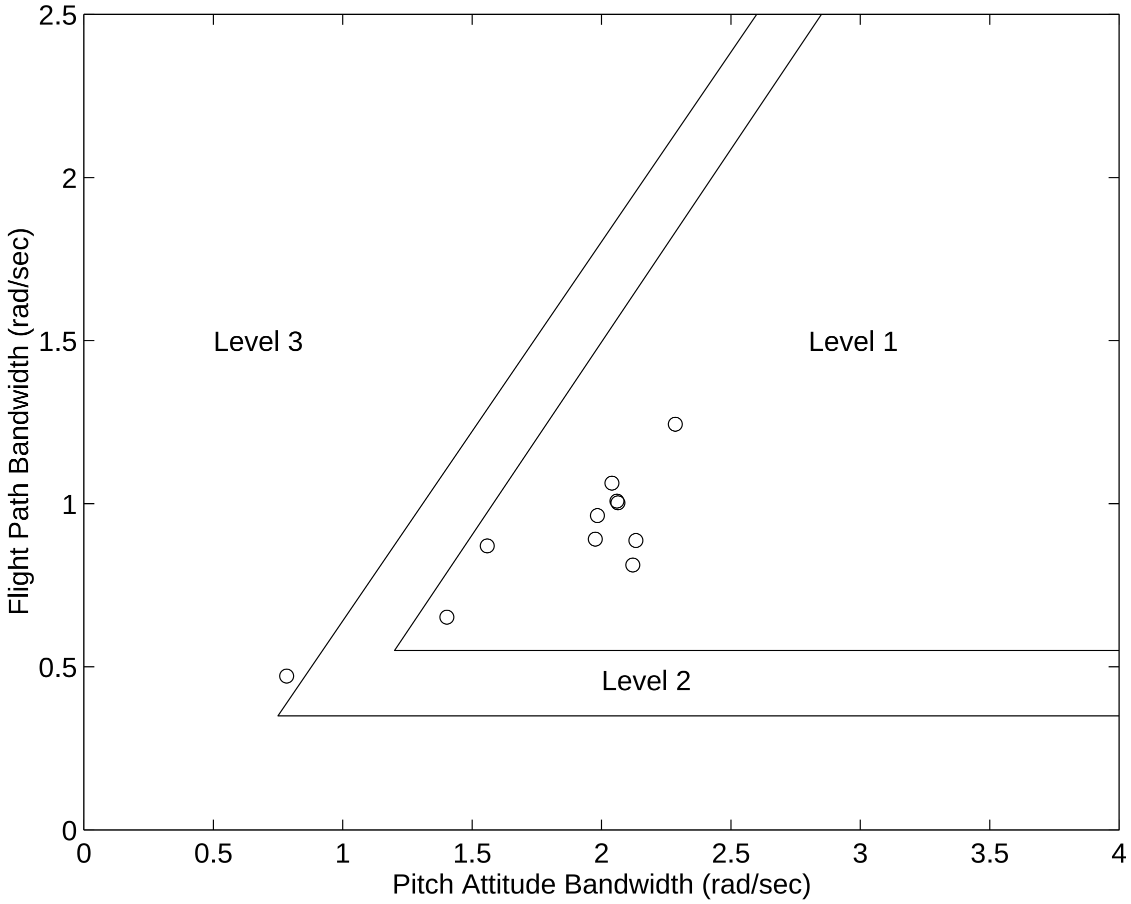


Figure 7.2: Pitch Attitude Bandwidth versus Flight Path Bandwidth for the Landing Flight Case (120 knots, flap 4)

are differences between these laws. Laws Base and 1 are angle of attack response characteristics where dropback has not been specifically designed for and therefore these will not have the desired dropback values. The pure rate-like laws (2, 4 and 6) all have dropback values of about 0.5 and hence the design was successful here. Adding trim to airspeed or trim to angle of attack affects the dropback, and with the trim to angle of attack laws it was particularly difficult to achieve the desired dropback value.

In addition, these laws were initially designed using a slightly different definition of dropback and therefore they have different values compared to the values listed here. All of the dropback measurements in this thesis were calculated using the same dropback method, see section 4.4. It can be also seen that the q_{max}/q_{ss} values are all around 1.5 where the dropback value is around 0.5.

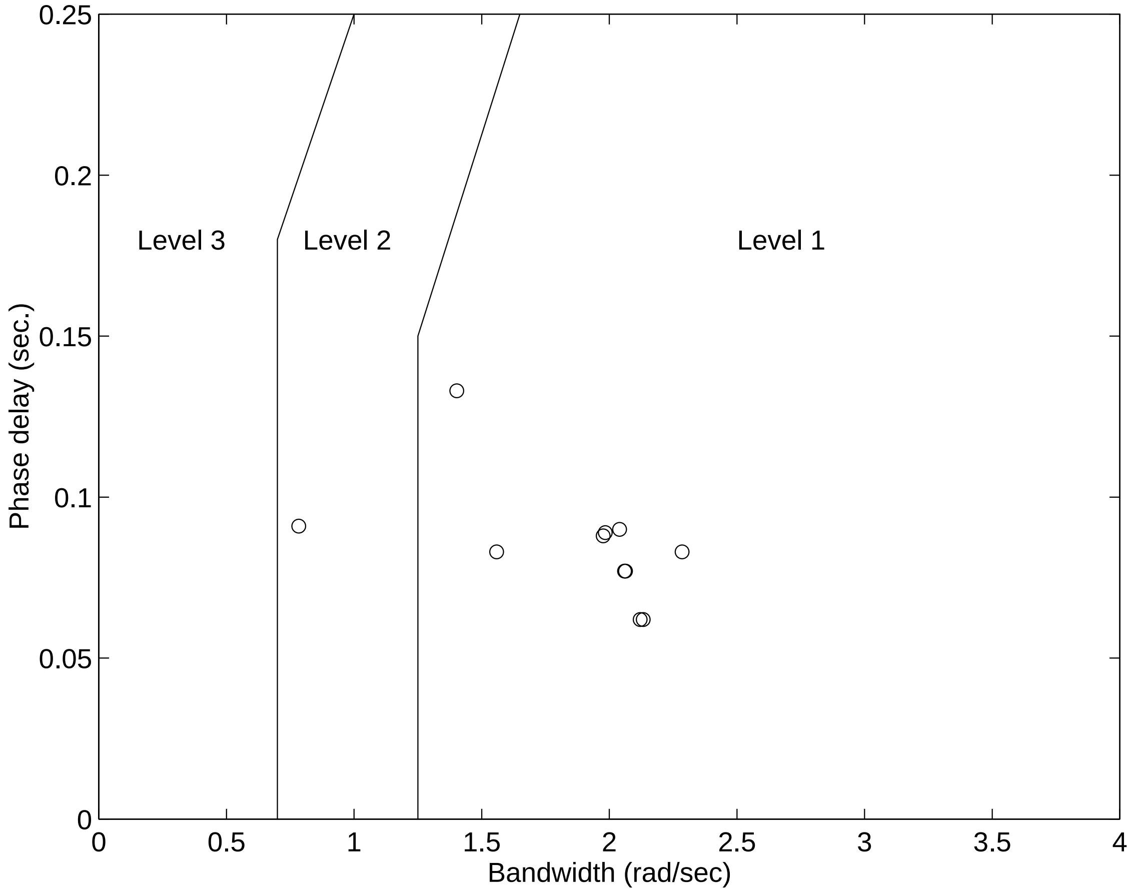


Figure 7.3: Pitch Attitude Bandwidth versus Phase Delay for the Landing Flight Case (120 knots, flap 4)

Short Term Mode Characteristics

From table 7.7, it can be seen that all of the short term mode damping ratios are approximately 0.7, but there is some variation in the short term mode natural frequencies to account for the requirement to design for a constant GCAP value.

Long Term Mode Characteristics

From table 7.8, it can be seen that the long term characteristics of the modes with static stability (whether through angle of attack or airspeed reference) are essentially of similar orders of magnitude. However, the damping ratios of the pitch rate laws are generally higher than those of the normal acceleration laws, and therefore the latter may require some additional form of long term mode damping.

Law	Dropback	q_{max}/q_{ss}
Base	0.6673	1.5442
1	1.8913	2.0696
2	0.5075	1.4704
3	1.9795	2.0253
4	0.6673	1.5442
5	1.7722	1.9801
6	0.5665	1.4141
7	1.9209	1.8171
8	0.8169	1.5277
9	1.1094	2.0162
10	2.0057	2.0560

Table 7.6: Dropback and q_{max}/q_{ss} Values for the Approach Configuration (120 knots, Flap 4)

	140 knots, flap 3		140 knots, flap 4		120 knots, flap 4	
	ω_{st} (rad/s)	ζ_{st}	ω_{st} (rad/s)	ζ_{lt}	ω_{st} (rad/s)	ζ_{st}
Base	0.900	0.583	0.940	0.555	0.747	0.6083
1	1.750	0.703	1.749	0.702	1.483	0.7012
2	1.751	0.706	1.756	0.702	1.501	0.6939
3	1.748	0.707	1.755	0.703	1.498	0.6961
4	1.759	0.702	1.770	0.706	1.492	0.7003
5	1.758	0.703	1.770	0.706	1.491	0.7014
6	0.904	0.741	0.909	0.753	0.762	0.7434
7	0.906	0.740	0.911	0.751	0.764	0.7424
8	1.564	0.737	1.885	0.756	1.564	0.7368
9	2.014	0.621	2.023	0.625	1.680	0.6288
10	1.207	0.735	1.231	0.749	1.243	0.5772

Table 7.7: Longitudinal Short Term Mode Characteristics

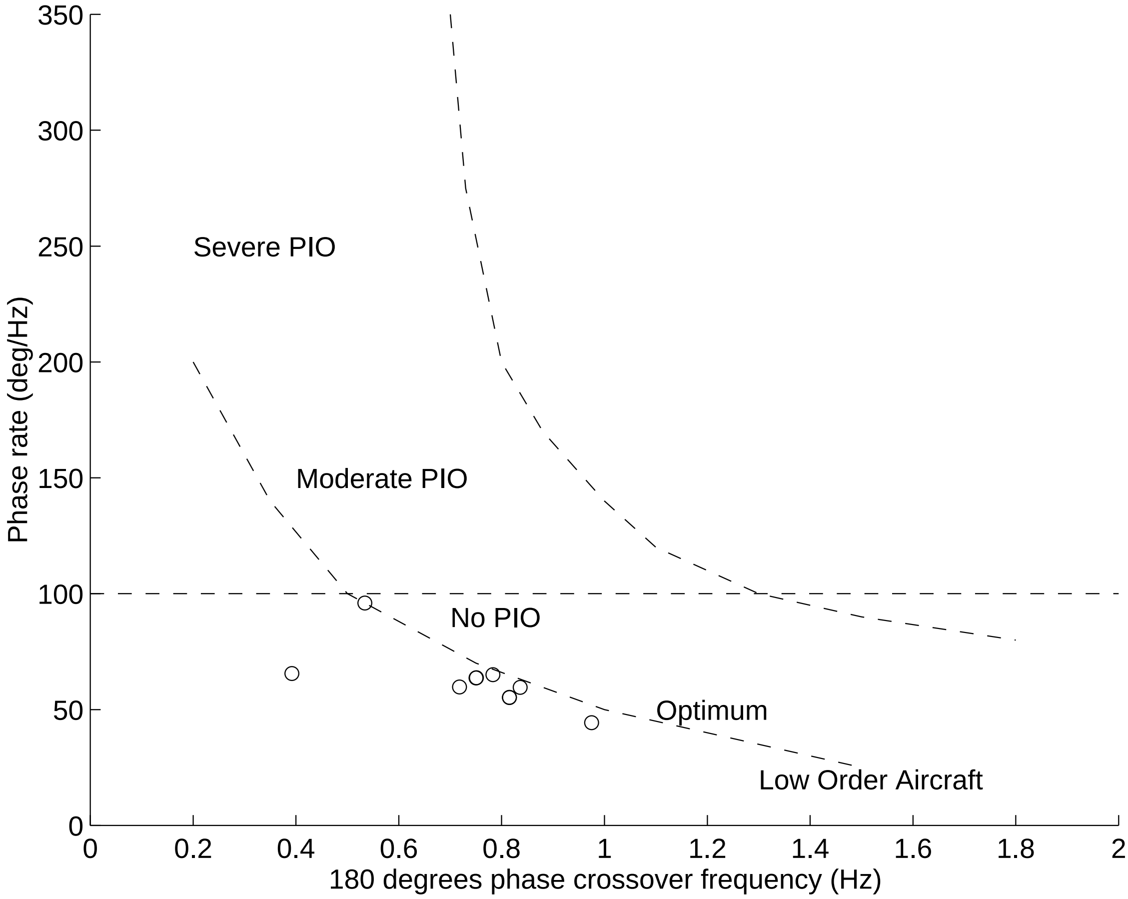


Figure 7.4: Phase rate versus Minimum Phase Crossover Frequency for the Landing Flight Case (120 knots, flap 4)

Sturmer's Pitch Sensitivity Criterion

The results from Sturmer's pitch sensitivity criterion may be seen on figure 7.7. It may be seen that all of the aircraft lie in the desired region, except for the baseline aircraft, which is the single line at the top of the plot. All of the aircraft presented here have an identical initial pitch acceleration of 0.6 deg/s^2/lb stick force.

7.5 Flying Qualities Experiment Results

This section contains the results for each of the aircraft flown during the evaluations. The results were recorded using the rating scales and comment cards which can be found in appendix C.1.

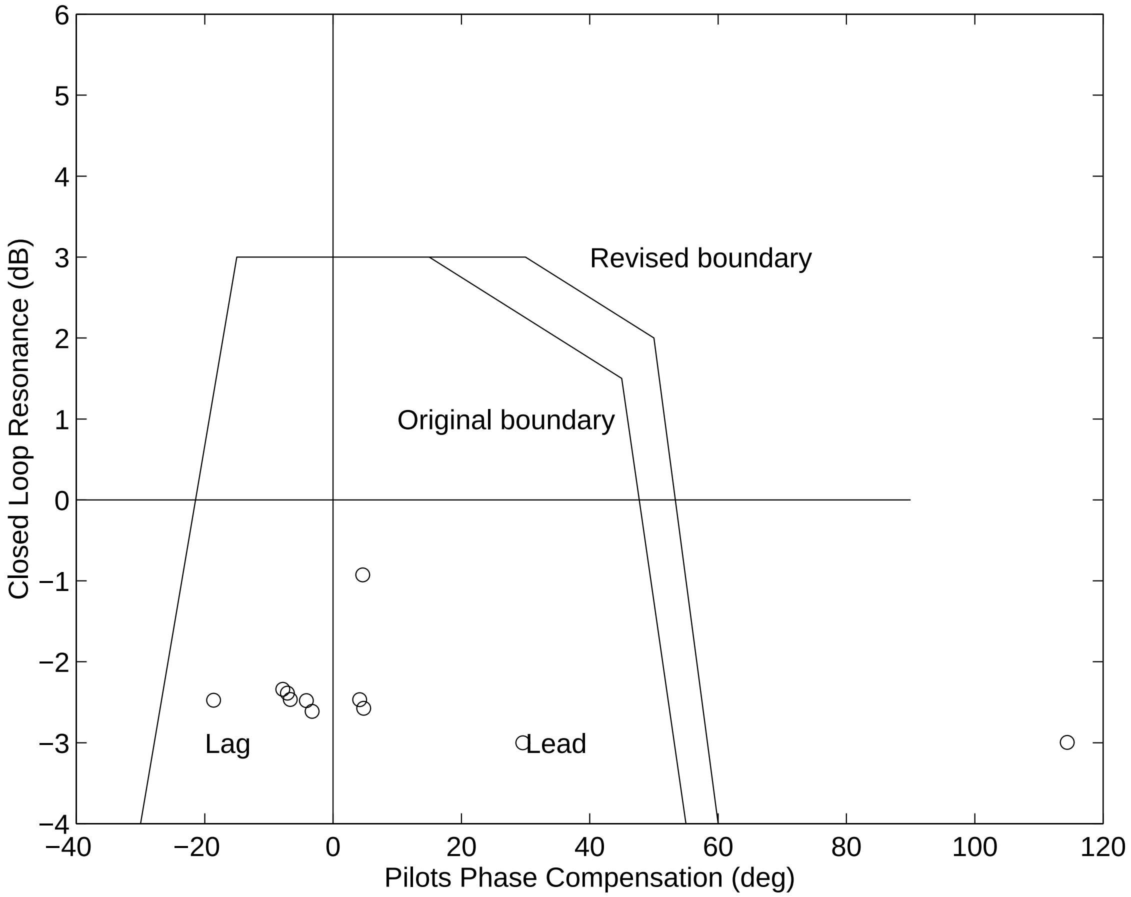


Figure 7.5: Neal-Smith Characteristics for the Landing Flight Case (120 knots, flap 4)

7.5.1 Evaluation Pilots

Four evaluation pilots took part in the evaluations. All are former RAF Test Pilots with previous flying qualities and large aircraft experience.

Pilot A - Roger Bailey.

After acquiring 5000 hours flying the C-130 Hercules for the RAF, he spent nearly 1000 hours as a flight instructor. After graduating from USAF TPS, he spent three years at RAE Bedford, nearly half as the squadron commander, primarily working on the Civil Avionics Programme, as well as working on Tornado and various Engineering Simulators. He took up his current position as the Chief Test Pilot at the Cranfield College of Aeronautics in 1990. Additionally, since 1990 he has flown the historic light aircraft of the Shuttleworth collection.

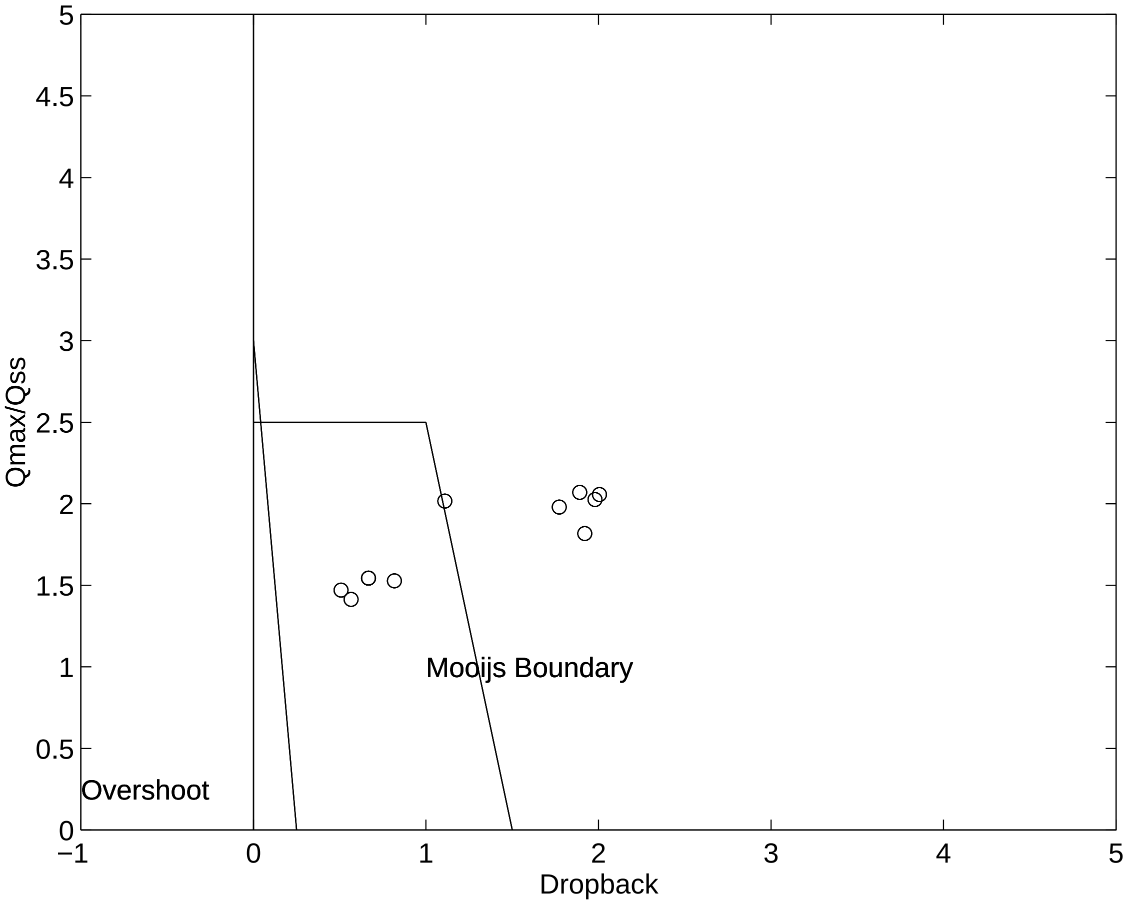


Figure 7.6: Gibson's Dropback Results

Pilot B - Mervyn Evans

After flying fast jets for the majority of his career in the Royal Air Force, he graduated from the US Navy TPS. He then served three years at RAE Farnborough, followed by three years as Principal Tutor, Fixed Wing at ETPS and two years as Principal Test Pilot at ITPS, Cranfield. He has considerable experience in fly-by-wire research and training, including involvement in the ETPS ASTRA Hawk and Calspan Learjet. He currently flies the Airbus A320 for Monarch Airlines.

Pilot C - Alan Foster.

After becoming a Qualified Flying Instructor in the RAF, he graduated from the ETPS at Boscombe Down. He then spent 6 years developing various fast jets. He left the RAF in 1985, and flew Boeing 727 for several years with Dan Air before joining British Aerospace as a test pilot in 1988. Since then, he has assisted with the development of both the BAe 125 and BAe 146/Avro RJ series of aircraft, and he is currently a test pilot at Avro International Aerospace within BAe.

	140 knots, flap 3			140 knots, flap 4			120 knots, flap 4		
	ζ_{lt}	ω_{lt} (rad/s)	T_{lt} (s)	ζ_{lt}	ω_{lt} (rad/s)	T_{lt} (s)	ζ_{lt}	ω_{lt} (rad/s)	T_{lt} (s)
Base	0.025	0.150	42.00	0.092	0.140	44.88	0.050	0.151	41.53
1	0.072	0.152	41.39	0.126	0.148	42.51	0.097	0.172	36.53
3	0.208	0.143	44.00	0.269	0.144	43.57	0.319	0.155	40.64
5	0.165	0.126	49.83	0.230	0.127	49.67	0.244	0.139	45.30
7	0.059	0.112	56.00	0.129	0.112	56.10	0.087	0.112	56.05
8	0.094	0.136	46.27	0.145	0.136	46.30	0.127	0.154	40.67
9	0.177	0.101	62.27	0.263	0.101	62.09	0.259	0.111	56.20
10	0.054	0.137	45.80	0.108	0.137	45.90	0.071	0.163	38.62

Table 7.8: Longitudinal Long Term Mode Characteristics

Pilot	Number of Control Law Types	Evaluations	Approaches
A	11	12	52
B	4	4	16
C	3	3	8
D	4	4	12
Total	11	23	88

Table 7.9: Evaluation Summary

Pilot D - Dan Griffith.

After acquiring 2000 hours flying mainly fast jets in the RAF, he graduated from the USAF TPS. After this, he was the project pilot for the VAAC Harrier at the DRA Bedford Aerospace Research Squadron, and also flew the BAC 1-11, Canberra and HS 748, before briefly spending time as a Test Pilot at Boscombe Down. He now has over 4000 hours, and is a Test Pilot at the CAA Safety Regulation Group.

7.5.2 Evaluation Summary

In total, 4 pilots made 88 approaches during at total of 23 evaluations with 11 different control law types. Approximately half of these approaches were made with the use of an autothrottle. Pilot A had two evaluation sessions, while Pilots B, C and D had a single evaluation session each. Table 7.9 gives a summary of these results.

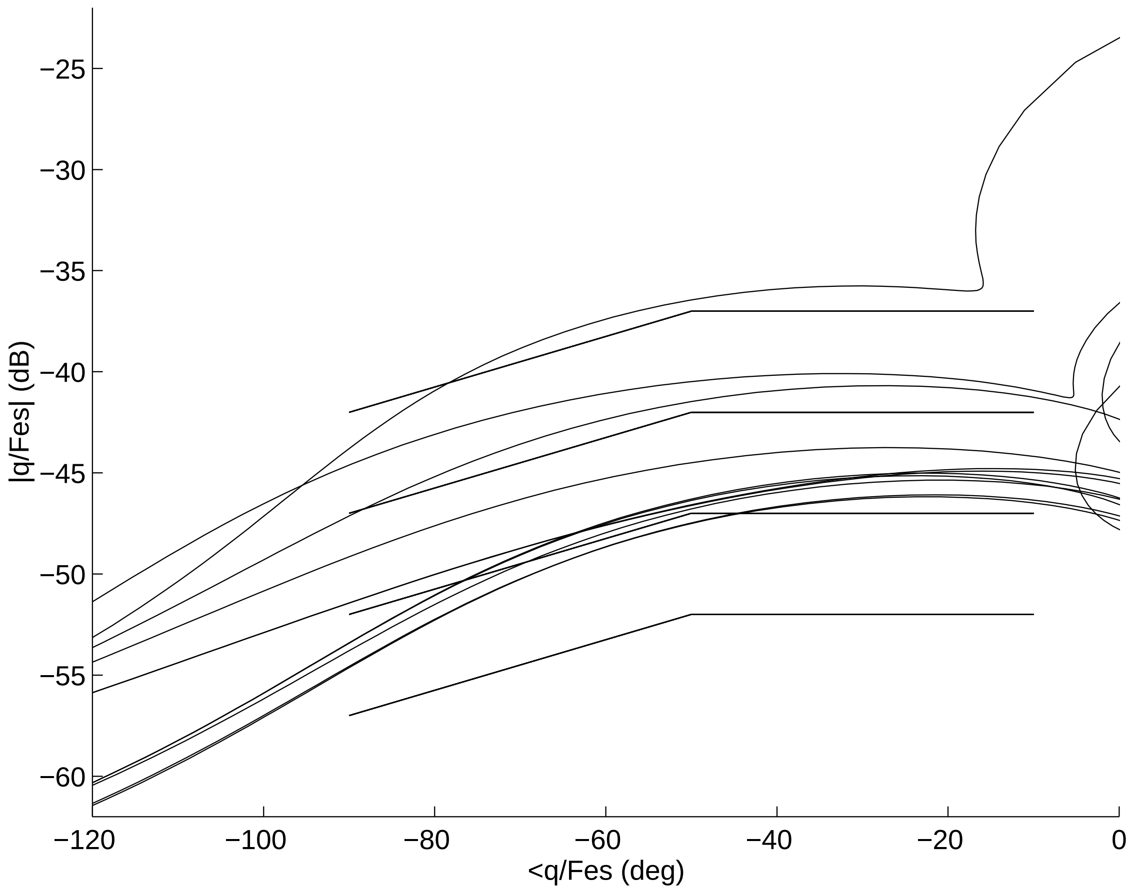


Figure 7.7: Sturmer's Pitch Sensitivity Criterion (120 knots, flap 4)

The evaluations were performed on the following dates

Session Number	Date
A-1	9th September 1996.
B-1	12th September 1996.
C-1	1st October 1996.
D-1	3rd October 1996.
A-2	9th October 1996.

In addition, a calibration session was carried out by the author during July 1996 to verify the simulator and control law performance. Minor modifications were made after that session, mainly to some of the control gains and to the implementation of the airspeed reference for the airspeed stable control laws. No problems were experienced with simulator performance during the evaluations, although the lack of visual and motion cues resulted in many of the landings being excessively firm.

7.5.3 Control Law Characteristics

This section summarises the flying qualities of each of the aircraft flown, i.e. the baseline (unaugmented) aircraft plus 10 control laws. Lateral or directional effects were not a factor in any of the evaluations. The Cooper Harper, Bedford Workload and PIO ratings are tabulated within appendix C.

Basic Aircraft

The basic aircraft was flown by all of the pilots and was used as a baseline reference against which all of the other aircraft were compared. The pilots were informed that this is how the aircraft would handle upon failure of the primary flight control system and therefore this aircraft was also used as the reference for the failure part of the flying qualities evaluations.

During the reconfiguration segment, this aircraft generally had low forces with desirable trimming characteristics. This aircraft had a mixture of CHR 3 and 4 from each of the pilots and all of the pilots perceived a heave in the flight path response.

During the approach, the pilot's comments confirmed that the aircraft had acceptable forces and trim characteristics. However, the aircraft is not solid in attitude and airspeed control was one of the more difficult features of this aircraft. This could have been due to a number of factors, one pilot commented on the excessive throttle to thrust gearing and comments were received concerning the displays, specifically the airspeed tape. Overall, the CHRs were a mixture of 3 and 4. The flare was rated better than the approach with CHRs of 2 and 3. The forces were appropriate and it was generally possible to control the flare parameters.

With autothrottle, the CHRs were generally degraded by about 1 point. This is due to the large pitching moment that occurs with power inputs because of the low slung engines and the active autothrottle, which generally holds airspeed well but is continually commanding power changes. The pilots found this disturbing during the approach due to the seemingly uncommanded pitching motions arising from the autothrottle.

Bedford workload ratings were generally 3 to 4 for this aircraft, and no great change was noted for the autothrottle. This aircraft was not deemed to be PIO prone in short term but there was a long term PIO due to the autothrottle effects.

Generally, this aircraft flew like a conventional aircraft, but lacked strong attitude stability, and the autothrottle caused quite a severe pitching moment which was detrimental to the task.

Augmented Angle of Attack (Law 1)

This aircraft was flown by one pilot and generally received CHRs which were one point better than the baseline aircraft. The response characteristics during the reconfiguration were better than the baseline, making the task easier. The trim characteristics were desirable and the airspeed control was similar to the baseline. The pilot thought that this aircraft had a slightly greater tendency to float compared to the baseline. This aircraft received almost identical Bedford ratings to the baseline aircraft.

The pilot commented that under the failure case, the pilot could not just be expected to cope, and would require some approaches at each base check. He commented that the most difficult part of the transition would be the flare, and the pilot may have a slightly increased workload in the case of loss of autothrottle. The main difference was the loss of attitude solidity.

Generally, this aircraft flew like a conventional aircraft, and was an improvement over the baseline aircraft, with no real problems likely to be experienced in making the transition under the failure case to the unaugmented aircraft

Pitch rate (Law 2)

This aircraft was evaluated by two pilots. It was found to be conventional during the reconfiguration task with a slight balloon up in flight path as the flaps deployed, giving CHRs of 4 due to the requirement to correct for the balloon. This aircraft was perhaps a little more responsive than previous aircraft, but this did not seem to reduce the ratings. One pilot gave a CHR of 2 for the approach and seemed to like the improved attitude solidness and found no problems with pitch attitude / flight path consonance (or relationship). The second pilot commented on the attitude stability, but gave the aircraft a CHR 4 due to the lack of trimming.

This aircraft requires the attitude-based flare law to avoid non-monotonic forces in the flare. The control forces were characterised as low but positive, and there was a need to hold a force in the flare. The flare itself was conventional and received CHR 2 and 3.

The autothrottle had a marked effect on workload reduction during the evaluation segment. However, there was a tendency for the aircraft to descend below the glideslope as the airspeed reduced. This is due to the nature of the control law. When the autothrottle is engaged, the airspeed reduced quite quickly, and therefore the pilots needed to steadily increase the angle of attack through increasing the pitch attitude in order to maintain lift and therefore the glideslope. If this did not happen then the aircraft would drop below the glideslope. In practice, a conventional autothrottle would not slow the aircraft down as quickly as the one designed for this aircraft, and the required increase in pitch attitude would be more gradual. The autothrottle had little effect on the CHR or Bedford workload rating, and this aircraft was not deemed to be PIO prone.

The transition from this control law to the unaugmented aircraft would probably be more difficult than the previous laws due to the lack of trimming with this law. This is quite a major change in philosophy, and therefore regular training would be required to enable the failure case to be coped with.

Generally, this aircraft flew well, and the pilots liked the solid attitude dynamics. However, there were flight path control problems on the approach due to the nature of the law, and it was unconventional due to the lack of trimming, which would make transitioning to the basic aircraft in the failure case more difficult.

Pitch rate with Trim to Airspeed (Law 3)

This aircraft was evaluated by two pilots. For the reconfiguration task, it required a conventional nose down input. The forces were light and appropriate, and there was no requirement to trim. It received CHRs of 2 and 3 for the reconfiguration. In the approach, it seemed to behave like a conventional trimming aircraft, with the response dynamics and feel system being about right. The second pilot flew it using a backside technique, where the airspeed was controlled with the stick, and the descent rate controlled with the throttles, although he commented that a conventional technique could be used.

For the approach, the trim to airspeed nature of the law, combined with the trim bug made the pilot very airspeed aware. In addition, it also gave this law a conventional feel, with much more attitude stability.

The flare was deemed to be slightly less light than some of the other corrections, resulting in a slight tendency to underflare. However, the pilot who made these comments tended to like lighter forces in the flare compared to the other pilots, and he also made the comment that he did not need to be careful.

The autothrottle also had a marked effect on workload reduction. This aircraft was rated CHR 2 for the autothrottle approach. The same flight path effect was found as with the pure pitch rate command system on the ILS.

The transition from this control law to the unaugmented aircraft would be easier than the pure pitch rate law due to the trimming requirement for this law. The pilot would probably find the unaugmented aircraft quite difficult due to the lack of pitch stability, but the transition would certainly be possible.

Pitch rate with Trim to Angle of attack (Law 8)

This law was evaluated by one pilot. He found that the trim rate was generally too slow, resulting in reduced ratings. Since this law had angle of attack stability, there was a requirement to trim for both flap and airspeed changes. He also found that it was a little too responsive, which led to over-controlling tendencies in the offset correction. No problems were experienced when the law was in trim.

The responsiveness results in the landing attitude being achieved a little too early, resulting in a floating tendency. Again, the autothrottle reduces the workload, but the problems with over-responsiveness and low trim rate still exist. It was this pilot's opinion that there would be no problem in making the transition to the baseline aircraft.

In general, this aircraft had acceptable dynamics, but there were problems with the low trim rate and also the slightly high responsiveness.

C* (Law 4)

The C* control law was evaluated by one pilot. He found the force for the reconfiguration pretty light, with conventional response characteristics and a CHR of 3. The approach also received a CHR of 3, with appropriate forces and a quick, but not abrupt response. The airspeed control was satisfactory, and the pitch attitude / flight path consonance was quite good. The flare also received a CHR of 3, with a flare which was very similar to being conventional. Again, this pilot did not like the lack of trimming.

Introducing the autothrottle reduced the workload, resulting in CHRs of 2 for both the reconfiguration and approach. The Bedford workload rating also improved for both of these tasks from 3 to 2. No PIO tendencies were noticed.

As with the pure pitch rate law, problems would be experienced in transitioning to the unaugmented aircraft in the failure case because the pilot would not be used to having to trim due to the lack of trimming, and loss in attitude stability.

In general, this was a non-trimming rate demand system with acceptable dynamics.

C* with Trim to Airspeed (Law 5)

This control law was evaluated by three pilots. For the reconfiguration task, the response was conventional, and there was no requirement to trim, although the aircraft still ballooned up, and therefore there was the requirement to correct for this. It received a CHR of 3 from every pilot who evaluated it.

For the approach, two of the pilots found the dynamics acceptable, with a solid feel in attitude, and no problems with airspeed control. There was also a requirement to trim to airspeed, which was conventional, although one pilot commented that there was not sufficient stick force with a given airspeed error to be of great assistance. However the third pilot found that this control law was 'confusing' and did not seem to fit into any defined category. This may have been due to the trim to airspeed system, which the pilot was not familiar with. Even so, it received CHRs of 2 and 3 for the approach.

In the flare, the control forces were fairly light, and it was deemed to respond well by two of the pilots, receiving a CHR of 2 from them. The third pilot found that he had to reassess the flare and make a second correction, and therefore awarded a CHR of 4.

The autothrottle was again found to reduce the workload for the task, and as with the pitch rate with airspeed trim law, the pilot would have similar problems in making the transition to the baseline aircraft, such as the lower attitude stability, and the lack of autothrottle.

In summary, this law had similar properties to the pitch rate law with speed stability, and has flying qualities close to an improved basic aircraft.

C* with Trim to Angle of attack (Law 9)

As with the pitch rate with trim to angle of attack, problems were experienced with the low trim rate for this aircraft. Two pilots evaluated this aircraft, and the comments were similar to those for the pitch rate with angle of attack trim law. These comments are reflected in the CHRs for the laws.

Normal acceleration (Law 6)

This control law was evaluated on five separate occasions by all four pilots and received the best overall ratings. For the reconfiguration task it held the desired flight path and therefore the only required pilot correction was an increase in thrust to offset the drag rise.

During the approach, the aircraft held the current fight path, even as the airspeed changed and therefore the required compensation as the airspeed decreased was negligible. This resulted in a very low workload and correspondingly low CHR. The stick forces and response characteristics were deemed appropriate, and the pitch attitude to flight path consonance was suitable.

The flare had the same characteristics as with previous pitch attitude flare laws. One evaluation pilot noticed a possible PIO problem in the flare, but later decided that it wasn't actually there.

The autothrottle provided for a very low workload aircraft, and resulted in the pilots being able to sit back and let the aircraft fly itself. This was noticed by several pilots. These aircraft (normal acceleration plus autothrottle) were the best rated of the whole evaluations, and received lowest workload ratings. However, some of the pilots were prone to letting the errors build up since they knew that they could easily correct them. Also, there was a tendency for the aircraft to pitch up by itself as it slowed down along the glideslope due to the angle of attack increasing to maintain lift. One pilot did not like this as he perceived it as an uncommanded pitch-up.

The comments concerning the flying qualities under failure indicate that this control law has flying qualities which are significantly different to the baseline aircraft. The requirement to trim and the significantly different response nature of this response type would result in the pilot operating with this law as the primary law experiencing the most problems in the failure case.

In general, this law is a very low workload law, but is non-conventional, and can result in the pilot sitting out of the loop. In addition, it has quite different characteristics to the unaugmented aircraft.

Normal acceleration with Trim to Airspeed (Law 7)

This law was flown by one pilot. He found that it had characteristics very similar to the basic normal acceleration law, but the requirement to trim for airspeed changes was favourable. However he commented that this law was not as nice to fly as the C*U or qU laws.

The control forces were very low during the reconfiguration, again with no requirement to trim. During the approach, the control forces and response characteristics seemed appropriate, with no problems experienced with either the aircraft slowing down or maintaining the glideslope. The flare was also conventional, with a slight tendency to float.

When the autothrottle was engaged, the workload was drastically reduced, and this is borne out in the Bedford ratings, and the requirement to retrim was liked.

The pilot commented that it would be 'quite a shock' transitioning to the unaugmented aircraft. The problem would be stabilising the flight path and pitch attitude, and the loss of the autothrottle would also make the task more difficult. Concurrency flying would be required.

In general, this law was semi-conventional in nature, assisted by the requirement to trim to airspeed. However, the benefits provided by flight path stability resulted in the aircraft being slightly non-conventional and it was not as nice as the pitch rate with airspeed feedback law to fly.

Normal acceleration with Trim to Angle of attack (Law 10)

This law was again flown by one pilot. As before, problems were experienced with the slow trim rate. The aircraft response during flap deployment was conventional, with light to moderate forces, but the slow trim rate hindered the task.

The control forces were also light and appropriate during the approach, with reasonable short term dynamics. As before, the slow trim did not help with the task. The flight path hold characteristics were favourable and no problems were experienced with pitch attitude / flight path consonance.

The pilot who flew this law considered the flare to be 'nice'. Initially he overflared, but by releasing the back pressure slightly he was able to lower the pitch attitude and land where he wanted to. He commented that it was nice to be able to do that and the aircraft was not PIO prone. No problems were experienced with airspeed control.

The primary effect of the autothrottle was to reduce the workload, and it had quite a large effect with this aircraft. The pilot made the comment here that he would have preferred to chop the power manually as the autothrottle did this automatically at 40 feet.

In the failure case, the difference between this aircraft and the baseline would not be too large. The pilot would probably be frustrated since he would not be able to fly as tightly as before, but the transition would be safe with continuation training.

In general, this law was semi-conventional, but it was hindered by the slow trim rate.

7.6 Discussion

This section contains the discussion of the results. It has been divided into discussion concerning the control laws themselves, and how they correspond to the criteria and related discussion areas.

Display Design

Comments were made about the displays, and were concerned with the following two areas. The first was the airspeed scale tape. Two pilots commented on the difficulty with using the tape, which was only made easier by the airspeed trend vector implemented.

The second main area of comment, which was made by all of the evaluation pilots was the lack of a flight path vector. These comments originated with the normal acceleration law, and the pilots wanted this vector to confirm the flight path. This type of display is relatively straightforward to design in theory, even if it has to be quickened by T_{θ_2}, but in practice it may be susceptible to turbulence and other atmospheric effects which can make is difficult to use and distracting, and therefore can be misleading.

Airspeed and Energy Awareness

Pilots comments were recorded concerning airspeed and energy awareness. The energy awareness was increased through the throttle position, and the lack of moving throttles with the autopilot significantly reduced the pilot's perceived energy awareness.

The airspeed awareness came from two main sources. The first was from the requirement to trim, especially with the trim to airspeed laws. The second source of information to assist with airspeed awareness came from the trim to airspeed bug. The airspeed at which the reference airspeed for the airspeed stability laws was displayed on the airspeed tape as a bug. One pilot in particular thought that this heightened the airspeed awareness since he could see exactly what airspeed he was trimmed at, and rated this as a very positive feature. However, other pilots did not comment on this and later comments from the pilot indicated that he was using it less and less. However, he stated it helped him to understand how the control law worked.

Limitations of the Evaluations

As previously stated, these evaluations were carried out in a fixed-base simulator with night visual graphics. This leads to some inherent limitations. Firstly, the lack of motion in the simulator can be a little misleading for an inexperienced evaluation pilot since the cues which are associated with motion are missing, which may lead to problems with flight path control. However, the pilots used for these evaluations were experienced in the use of fixed-base simulation for flying qualities investigations, which would have reduced the effects due to the lack of motion to a minimum.

Secondly, the limited night visual graphics combined with a limited field of view (no more than 50 degrees from the centre of the picture on one side, and approximately 30 degrees on the other) resulted in a lack of cues to the aircraft sink rate, especially in the flare, which meant that most of the landings could, at best, be classified as hard. The lack of a touchdown jolt also did not assist in the perception of the sink rate at touchdown.

Finally, the fact that these investigations were not being carried out in flight reduced the anxiety associated with flight, and this would have had an effect on the evaluations.

The lack of moving throttles during autothrottle operation caused some reduction in pilot energy awareness. Unfortunately the throttles had to be non-moving due to the simulator hardware setup. This was probably a factor in some of the autothrottle evaluations. In addition, one pilot (who is actually the development pilot for the aircraft under consideration) commented on the high throttle movement to thrust gearing, which was excessive. This may have caused problems in airspeed control for some of the other pilots, although it was constant throughout the evaluations.

Atmospheric disturbances were not included since the idea for these evaluations was to isolate the basic characteristics of the control laws. However, the design of good control laws which are resistant to atmospheric disturbances is not a trivial task, and will need to be considered for later studies.

Due to the limited length of the evaluation sessions, the evaluations had to be performed reasonably quickly. This did not cause too many problems for these evaluations, but when the number of control laws is reduced, longer evaluations for each law will be feasible.

Response Characteristics

The previous paragraphs show that the pitch rate based demand systems give essentially classical responses which are similar to those for the unaugmented aircraft in the short term, and the introduction of airspeed based static stability gives classical long term responses. Normal acceleration demand systems give non-classical responses, often in the opposite direction to a classical aircraft, with static stability sometimes giving a reversal in the direction of the aircraft pitch attitude response, which is undesirable due to lack of predictability.

Field also found that the absence of trim changes with airspeed are mildly frustrating to the pilot in the A320, especially where the pilot felt as though he should be trimming. He found that the requirement to trim with configuration change in the short term, and particularly airspeed changes in the longer term are a useful and positive cue to the pilot.

Aircraft Dynamics

The short term mode natural frequencies for pitch rate, C* and angle of attack were higher than those for the normal acceleration control laws. This has been seen before, but not explained. The author believes that it is due, in this case, to having to design for a constant value of GCAP, and this is borne out by the evaluations, as none of laws 1-7 received any serious complaints about the characteristics of the response. Therefore the use of a Generic CAP value as a design tool has been borne out here. One pilot thought that the normal acceleration law may have been PIO prone in the flare, but after a couple of attempts to land the aircraft decided that it wasn't. The steady state forces in the flare were very close to those of the other pure rate laws with attitude-type response dynamics in the flare, and therefore it is postulated that this 'ghost PIO tendency' was due to the lower short term mode natural frequency of this law.

The GCAP work also explains why CAP, in its conventional form has been reasonably successful with the pitch rate response type. Analysis of table 7.7 shows that for a reasonably constant value of GCAP, the short term mode natural frequencies of the angle of attack and pitch rate systems are more or less identical. There is one caveat here though - all of the control laws used for this evaluation were designed using a proportional-plus-integral controller, and using a second order mode with a 0.7 damping ratio as the short term mode response. If the short term mode response had first order characteristics then CAP probably could not be applied.

Many evaluations have been carried out using pole placement methods. These enable a wide range of response characteristics to be examined. However, they can have problems. Analysis of previous studies carried out showed that no account was taken of dropback, and in some cases there were excessive amounts of dropback ($\pm$ 10 seconds, where the limits proposed by Mooij are approximately -0, +1.5 seconds). Therefore this could have clouded the results. However, limits were specified on dropback for these laws.

In summary, a small amount of dropback (0.5 seconds) in the landing configuration reduces the effective flight path delay parameter (t_γ), which seemed to assist the pilot in the flight path control task, see section 4.4. Indeed, this was incorporated in all of the laws, and no problems were experienced with the pitch attitude to flight path consonance. Therefore dropback is justified as a criterion for use in the design process as it helps to fine tune the flight path response.

No problems were experienced with the value of the short term mode damping ratio selected, and therefore 0.7 seems to be a suitable value.

The long term dynamics were not explicitly specified in the design process, although it was verified that they were stable. It seems that the value of about 3.2 knots per pound stick force was suitable for the approach - it gives the pilot some feel that he is off airspeed, yet does not give a long term mode frequency which is excessive (approximately 12 times slower than the short term mode, which is a suitable separation), and does not seem to be high enough to degrade the glideslope tracking as NLR found (see section 6.5).

No problems were experienced with short term Pilot Induced Oscillations. Several pilots found that there was a long term oscillation with the autothrottle engaged due to the sensitive nature of the autothrottle, though this was not deemed to be dangerous. This lack of short term PIO is to be expected since all of the laws meet the published phase rate criterion which has been shown to be a good indicator of PIOs, see figure 7.4.

Flying Qualities under Failure Issues

It is considered relatively easy to maintain two very different motor skills such as flying an aircraft and driving a car. It is also considered relatively straightforward to maintain a skill when one has many thousands of hours using that skill. One example of this is an experienced driver or airline captain, who will not have to fly as much as a very junior or inexperienced pilot / driver to maintain proficiency. However, it is very difficult to maintain two similar skills, such as flying two aircraft which are quite close, such as a large aircraft and a small light aircraft, or an aircraft where two different piloting techniques are required since they can become confused within the mind of the pilot.

Comments made by the evaluation pilots concerning the nature of the change from the augmented to the unaugmented aircraft are as follows:

- *Angle of Attack* In going from the normal to the direct mode, the pilot would have little difficulty, except that the direct law aircraft is very much looser in attitude;

- *Pitch rate or C* or Normal Acceleration with airspeed reference* The pilot would have some more trouble than angle of attack due to the very desirable nature of these control laws, and he would be frustrated with the deficiencies in the trimming system as well as the lack of attitude solidity with the basic aircraft. However, the pitch rate response characteristic is still comparable with a conventional aircraft;

- *Pitch rate or C** The pilot would have more trouble than with the previous aircraft, mainly having to learn to retrim the aircraft very quickly, and also due to the lack of solidity in attitude. However, the pitch rate response characteristic is still comparable with a conventional aircraft;

- *Normal acceleration* The pilot would have the most trouble with this aircraft due to the normal acceleration response type being different to the pitch rate-like behaviour of a classical aircraft, and also due to the fact that he would have to learn to retrim.

These comments do not mean that any of the laws are unsuitable in any way, indeed the Cooper Harper ratings show this not to be the case. However, they do indicate that in emergency situations, the pilots would have more problems reverting to the normal acceleration or pitch rate / C* response types as opposed to the C*U / qU or angle of attack response types.

Work has been performed as a part of a GARTEUR Action Group to investigate handling qualities for future transport aircraft [103]. One of the main conclusions from this work was that the changeover from primary to backup systems at flight control system failure should not result in a large step increase in workload and pilot compensation, and the degradation in system sophistication should be acceptable by the pilot. This backs up the findings in this study, where the systems in which the transition is easiest from primary to backup have the lowest change in handling characteristics. However, further comments indicated that the pilots did prefer the normal acceleration law and would accept the increased workload due to it.

Hence from a failure point of view, the fly-by-wire law would ideally be classical in nature, not because the other response types give particularly bad flying qualities, but because the aircraft needs to be flyable in the presence of the past experience of its pilots, and there should be no significant changes in the flying qualities in failure situations. However, comments from the pilots stated that they would rather have the more unconventional control laws, and accepted that although the transition may be a little more difficult, it would be acceptable.

7.7 Summary Conclusions

- A set of law independent control law design requirements may be used to successfully design control laws;
- The normal acceleration law had the lowest workload and received the best Cooper Harper rating due to its low workload and ability to hold flight path, though it does require a non-conventional piloting technique;
- The pitch rate law with trim to airspeed gave the most conventional feel with good attitude stability and good airspeed awareness. The normal acceleration law with airspeed feedback did not give quite such a conventional feel;
- The use of a Generic Control Anticipation Parameter (GCAP) has initially been shown to be successful and applicable to both conventional and non-conventional control laws;
- The use of an autothrottle has a significant effect on the workload and airspeed control, and is more favourable for flight path stabilisation control law than for a low augmentation angle of attack-based law;
- More work is required to look at a tighter flight path control task and atmospheric disturbances;
- An aircraft which handles in a conventional manner is the most suitable from a flight control system failure point of view due to the small change in aircraft flying characteristics, though for all of the rate-like characteristics tested, reversion to the baseline aircraft was possible.

8 Evaluation of Approach through Windshear and Formation Flying Tasks

Further to the work carried out in Chapter 7, this Chapter describes a number of flying qualities evaluations looking at a windshear approach and formation flying tasks. For a more detailed description of the flying qualities criteria used, see reference [58] and Chapter 7.

8.1 Effects of Windshear

This section demonstrates how the effects of windshear (which for the purposes of these evaluations is a horizontal wind gradient) affects the performance of the aircraft. Consider an aircraft flying through windshear whilst established on an Instrument Landing System (ILS). The pilot (or autopilot / autoland system) attempts to maintain the airspeed at an appropriate value (nominally $V_{REF}+5$ knots) and also on the glideslope in the presence of disturbances.

The ILS glideslope and localiser define a flight path with respect to the earth reference frame, and the inertial (or earth) position of this path is not dependent on the local wind velocity or direction. The pilot attempts to maintain this inertial path in the presence of disturbances. However, the pilot will see the effect of a steady wind in the difference between airspeed and groundspeed, and also heading angle and track angles. For example, if the aircraft is flying in straight and level flight directly into a 10 knot headwind, the groundspeed will be equivalent to the airspeed, less 10 knots due to the wind effect.

The effect of the wind on the effective flight path angle can be found in the following derivation. The effective flight path angle is the inertial flight path angle which the aircraft would follow if it was flying in zero wind conditions, assuming it is flying along an actual inertial flight path angle in the presence of a specified headwind and a specified wind shear. Newton's second law states:

$$Force = Mass \times Acceleration \tag{8.1}$$

In this case, the acceleration is measured in the inertial frame, i.e. earth reference frame, and all forces and accelerations must be resolved with respect to this reference frame. This is a fundamental fact, which has important consequences on the aircraft during windshear, since the effects of wind effectively disconnect the aircraft's airspeed from its inertial speed (or groundspeed).

Using the above information, it becomes apparent that as the headwind component decreases, the airspeed decreases for a constant inertial or earth reference (ground) speed. Since the pilot is attempting to hold a constant airspeed, he will therefore need to accelerate the aircraft with respect to the inertial reference (i.e. the earth) to maintain the airspeed.

Resolving the forces along the flight path,

$$Acceleration = \frac{Resultant\ Force}{Mass} \tag{8.2}$$

Therefore

$$\dot{V_{air}} + \dot{W_X} = \frac{T - D + mg\ sin\gamma_i}{m} = \dot{V}_{Groundspeed} \tag{8.3}$$

$$\dot{V_{air}} + \dot{W_X} = \frac{T - D}{m} + g\gamma_i \tag{8.4}$$

where T is the thrust and D is the drag, both assumed to act along the flight path. m is the mass of the aircraft, V_{air} is the airspeed, W_X is the horizontal headwind which is assumed to be parallel to the direction of flight, and γ_i is the earth reference flight path angle. This effectively states that the aircraft must be accelerated in the earth reference frame at the same rate as the headwind component decreases to maintain airspeed ($\dot{V_{air}} = 0$). These symbols can be found in figure 8.1.

Therefore, in straight and level, unaccelerated flight, where $\dot{W_X} = 0$ and $\gamma_i = 0$,

$$\dot{V_{air}} = \frac{T - D}{m} = 0 \tag{8.5}$$

Therefore, for constant airspeed, thrust and drag and for a non-zero horizontal wind gradient,

$$\dot{W_X} = g\gamma_{esh} \tag{8.6}$$

where γ_{esh} is the change in effective inertial flight path angle due to the wind shear, or in other words, the aircraft will climb in the inertial frame in the presence of positive wind gradient, compared to the basic airframe. This then gives an effective inertial flight path angle which must be maintained to penetrate the wind gradient.

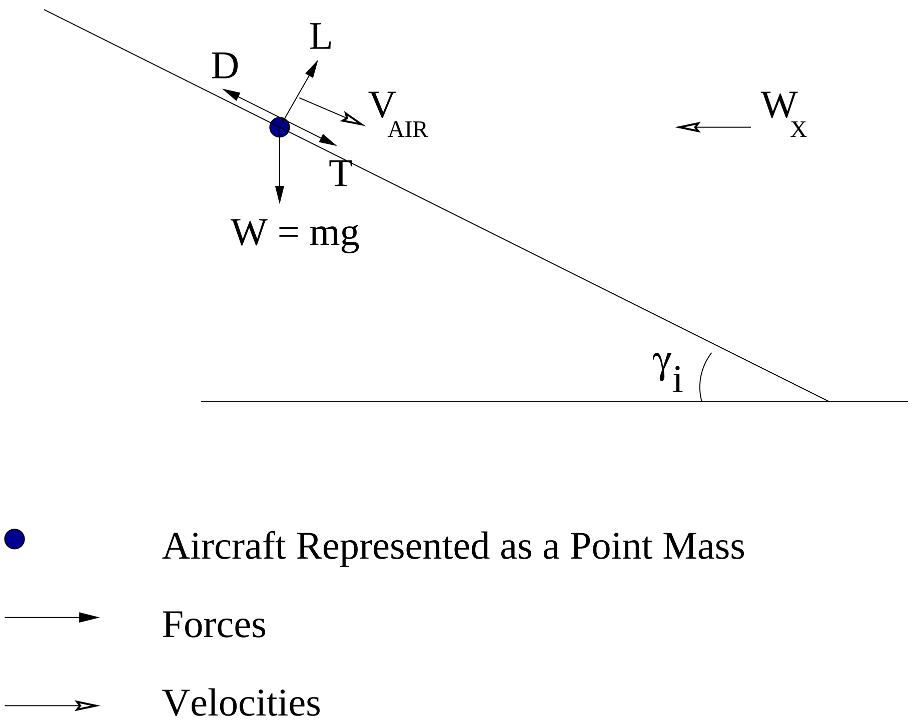


Figure 8.1: Symbols Used for the Windshear Analysis

Consider the next case, with a steady headwind gradient. For an aircraft to follow an effective earth reference flight path, it must follow an aircraft-reference flight path, as shown by the following formula.

In inertial references,

$$tan(\gamma_i) = \frac{Inertial\ Rate\ Of\ Climb}{Groundspeed} \tag{8.7}$$

The effective flight path angle as experienced by the aircraft is defined as follows:

$$tan(\gamma_{est}) = \frac{Aircraft\ Rate\ Of\ Climb}{Airspeed} \tag{8.8}$$

Finally, The airspeed and groundspeed are related by the following formula:

$$Groundspeed = Airspeed - Headwind\ Component \tag{8.9}$$

Assuming the flight path angles are small and since the Aircraft Rate Of Climb is equal to the Inertial Rate Of Climb in a headwind,

$$Airspeed \times \gamma_{est} = Groundspeed \times \gamma_i \tag{8.10}$$

Finally, since Groundspeed and Airspeed are related by equation 8.9,

$$Airspeed \times \gamma_{est} = (Airspeed - Headwind\ Component) \times \gamma_i \tag{8.11}$$

Therefore, substituting V_{air} for Airspeed and W_X for Headwind Component, and rearranging,

$$\gamma_{est} = \gamma_i \times \left(1 - \frac{W_X}{V_{air}}\right) \tag{8.12}$$

In the limiting case, where the headwind has the same magnitude as the airspeed, the effective flight path angle will be zero, since the aircraft will not be descending, while the earth reference flight path angle will still be as before (-3 degrees for an ILS), since the aircraft will not be making any horizontal progress.

Therefore the effective aircraft flight path angle is the sum of the previous two components.

$$\gamma_{eff} = \gamma_{est} + \gamma_{esh} \tag{8.13}$$

i.e.

$$\gamma_{eff} = \gamma_i \times \left(1 - \frac{W_X}{V_{air}}\right) + \frac{\dot{W}_X}{g} \tag{8.14}$$

Therefore, for a given steady-state headwind, a given required inertial flight path angle and a given wind shear rate, the effective flight path angle may be calculated, i.e. the flight path angle that the aircraft would fly along if the aircraft was removed from the headwind / wind shear condition, and placed in a stationary atmosphere with an identical airspeed and power setting.

8.2 Flying Qualities Experiment Design

The same requirements on the flying qualities experiment design are used as those in section 7.2. These evaluations have been used to examine control law performance in the following areas.

1. The effect of a decreasing headwind;

2. The ability of the pilot to perform a tight flight path control task.

This section describes the two tasks used for the flying qualities experiment described within this Chapter.

8.2.1 Windshear Approach Task

For this evaluation, the pilot was required to perform an ILS approach task in the presence of a decreasing headwind. The evaluation task used comprised the following segments, and the flare component can be seen in figure 8.2.

1. Start at 3 miles and 140 knots ($V_{REF} + \approx 20$ knots) configuration 4, and at 900 feet above aerodrome level. The aircraft is therefore fully established on the Instrument Landing System (ILS) and when released, it continued to maintain the ILS localiser and glideslope. The aircraft was initially flown along the ILS in this configuration and the pilot was briefed to slow the aircraft down to 121 (V_{REF} + 5 knots) by 300 feet AAL, requiring a reduction in power setting and possibly a pitch input.
2. At 300 feet, the pilot was briefed that there would be a decreasing headwind shear, the headwind at 300 feet being 30 knots, while the headwind below 50 feet AAL was 0 knots. The pilot was asked to maintain the glideslope and airspeed during this segment, requiring a marked increase in power and possibly a pitch input.
3. The final part of the task was to flare and land within the marked touchdown zone, requiring a reduction in power to idle and a pitch input.

This evaluation segment was repeated a number of times. The evaluation pilot was initially given two or three approaches with the unaugmented (baseline) aircraft to familiarise himself with the procedure. He then carried out either 2 or 3 approaches with the control law under consideration, and then the pilot and test administrator completed the pilot comment card.

8.2.2 Formation Task

For this part of the evaluation, the pilot was required to perform an in-flight refuelling / formation flying task. The evaluation pilot was flying the receiver aircraft, with the tanker flying a little ahead at constant airspeed, heading and altitude. The evaluation task used comprised the following segments:

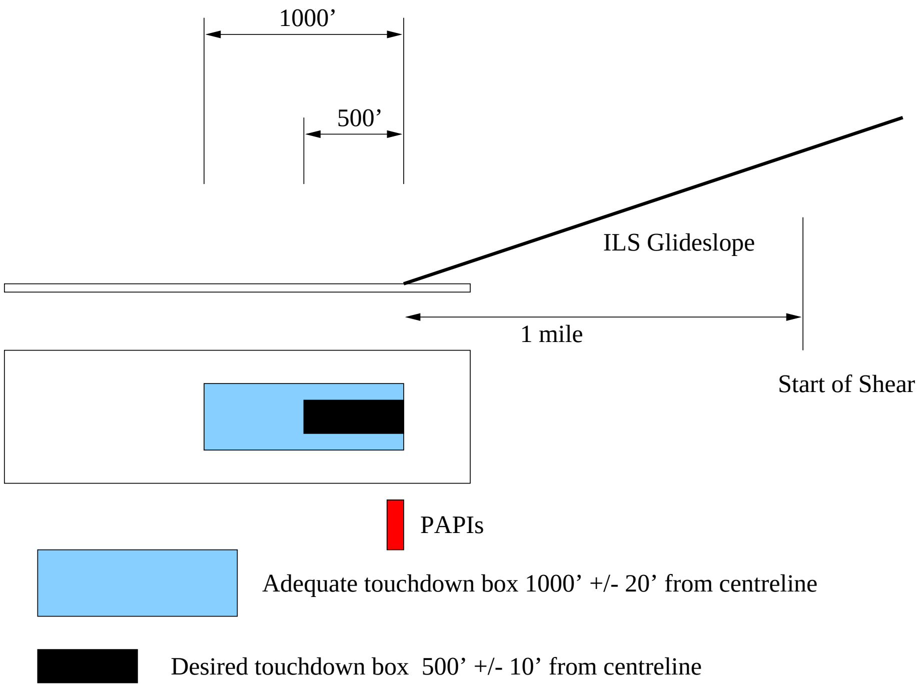


Figure 8.2: Approach Evaluation Procedure Used

1. Start at approximately 1180 feet behind the aircraft on which the formation task is to be performed, 250 feet below, and at the same airspeed and heading. The view behind the receiver aircraft can be seen on figure 8.3.

2. Accelerate to climb and close the distance behind the tanker. The distance at which the formation lights illuminate can be seen on figure 8.4, and the colour code for the lights can be seen on figure 8.5. This initially required a power increase and pitch input, and then a power reduction and an additional pitch input to stabilise behind the tanker.

3. Maintain the position for a period of at least two minutes from when the receiver was first stabilised within the defined limits. This required coordinated movements in all three axes and also in throttle. An airbrake was available for use if required.

The tanker was programmed to be a silhouette which was dark in colour (against the slightly lighter sky) but was effectively translucent. A box of lights (described in the next paragraph) was mounted on the tail of the tanker (on the aircraft centreline), and there was also a line of lights running from the tail to the nose of the tanker. Finally, a tail light (actually at the centre of the box) and two wingtip lights were mounted on the tanker, and these were used for formating on the tanker. These lights were visible above the distance at which the other lights started to illuminate (nominally 1180 feet), and gave the pilot sufficient cues as to the orientation and position of the tanker.

The arrangement of lights requires some explanation. It was designed to give the pilot a measure of both his position in relation to the centreline of the tanker, the distance from the tanker (including the distance from the ideal position) and also a measure of the rate of closure in relation to the tanker. The lights were arranged so that when the pilot was closer than the distance at which the light illuminated, the light would be on.

The pilot was briefed with the following desired and adequate performance bounds. The total task duration was 2 minutes. For the lateral and vertical task, the pilot was briefed that if the aircraft centreline lights remained within the box for more than 90 seconds then the performance was desired, if the centreline lights remained within the box for 30 to 90 seconds the performance was adequate, and if the centreline lights were in the box for less than 30 seconds the performance was less than adequate. A similar set of timings was used for the distance task, except that the desired distance was defined as being between 75 and 105 feet behind the tanker, i.e. with any number of the amber lights illuminated, all of the white lights illuminated, and none of the red lights illuminated.

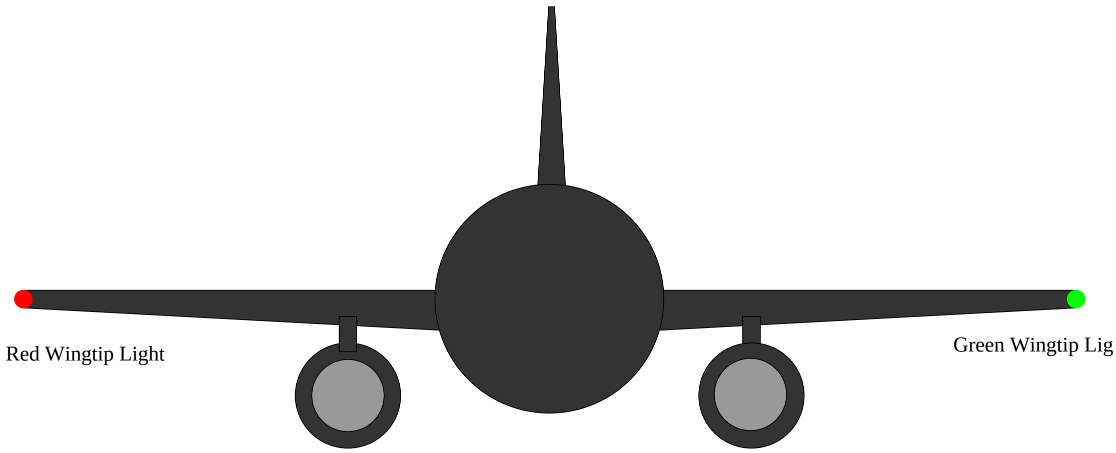


Figure 8.3: View from the Receiver Aircraft

This evaluation segment was flown once. The evaluation pilot was initially given a practice approach with the unaugmented (baseline) aircraft to familiarise himself with the procedure. After the task the pilot and test administrator completed the pilot comment card.

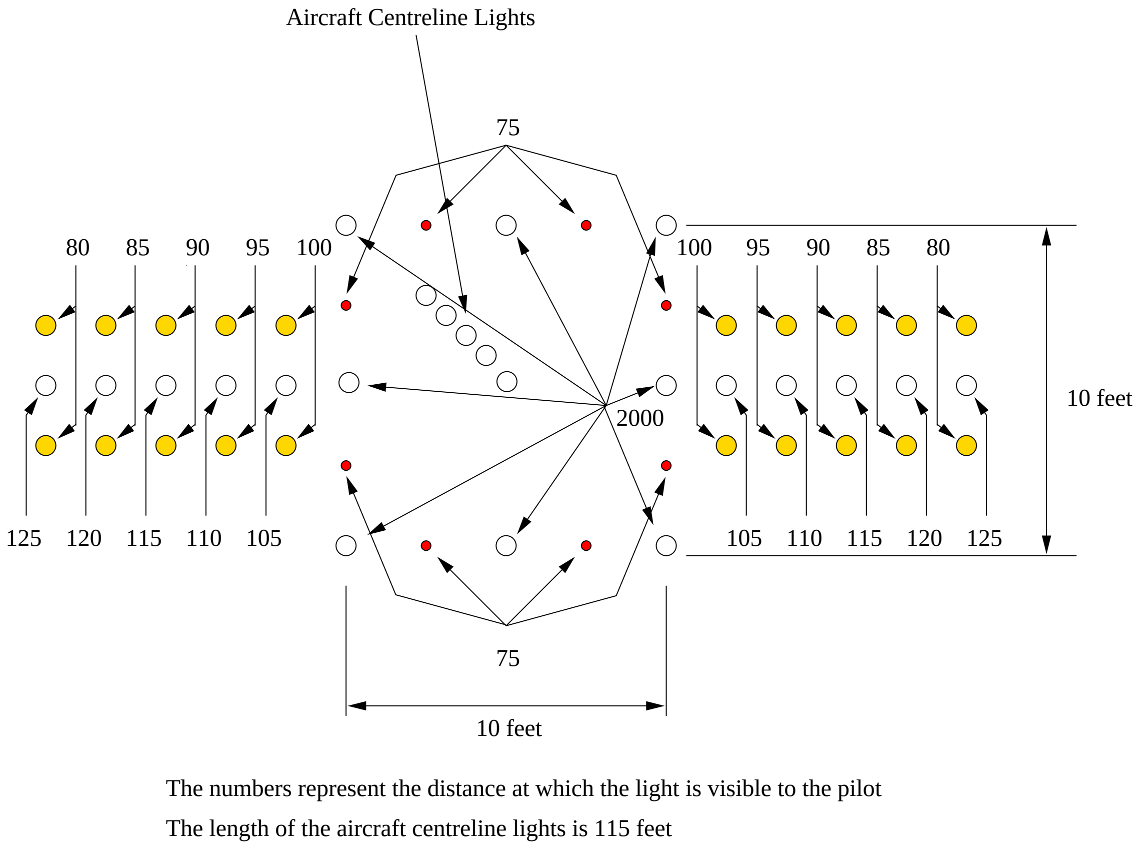


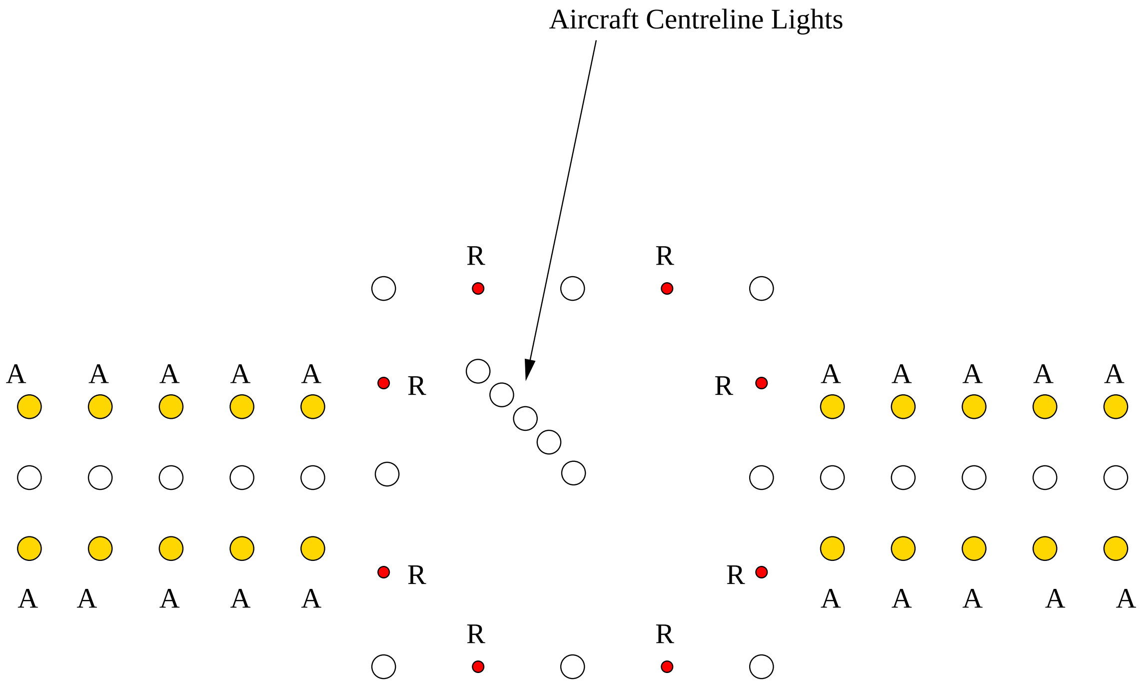
Figure 8.4: Distance at which the Formation Lights Illuminate

8.3 Control Law Design Criteria Modifications

The design requirements described in section 6.3 were used, subject to some minor modifications. These modifications were made from the results of the evaluations described within Chapter 7.

- An airspeed stability level of 4 knots /lb for all flight cases for control laws where airspeed stability is required;
- A non-monotonic flare characteristic;
- Stick re-datuming with trim for all flight cases;
- The angle of attack trim rate was modified to give a more suitable rate.

These are intended as strict guidelines, but due to problems with designing complex control laws such as these, a slight error was tolerated on these parameters for the



Colour Code for the lights :

White	No code
Red	R
Amber	A

Figure 8.5: Colour Codes for the Formation Lights

final control law designs. The major difference from the previous set of evaluations in the requirements and designs are listed below.

1. The airspeed stability level was decreased from the previous set of evaluations. This modification was made since problems were experienced with the long term mode damping at the higher static stability levels and higher airspeeds, and the results suggested that the amount of airspeed stability used may have been greater than the optimal.

2. The long term mode damping ratios were increased. The major effect of this was seen at higher airspeeds with the normal acceleration and normal acceleration with trim to airspeed laws.

3. Pitch attitude feedback was used. This increased the long term mode damping.

4. For the pitch rate demand law, the forces were increased in the flare to reflect

the pilot comments from the previous evaluations. The forces in the flare with the airspeed feedback law were reduced to the decreased airspeed error feedback gain.

5. The short term mode natural frequency was increased at constant values of dropback and GCAP.

The laws produced using this process were similar to the laws designed for the first set of evaluations, since the improvements were essentially incremental. The control law gains for these control laws are contained within reference [92]. Problems experienced with a low long term mode damping were addressed through the use of pitch attitude feedback which cured the problem in a satisfactory manner.

Stick Datum

Stick datuming was added in the following way. For the unaugmented aircraft (law 0), and the augmented angle of attack (law 1), the existing feel system was retained, and is described within section 7.1. This datumed the control wheel in proportion to the horizontal stabiliser position.

For the positive airspeed stability control laws, the stick datum was moved as a function of the trimmed reference airspeed. The zero datum reference speed was 180 knots (i.e. with the stick datum in the mid-point), and a reference gradient of 30 knots/inch was used, i.e. a trimmed airspeed of 120 knots gave a datum position of 2 inches aft of the mid point.

For the angle of attack laws, the stick datum was moved as a function of trim reference angle of attack. The zero datum angle of attack was 2 degrees, and a subsequent gradient of 2 degrees per inch was used, i.e. a reference value of 8 degrees gave a stick datum position of 3 inches aft. This gave movements which were comparable to the trim system for the baseline aircraft, with a slightly greater movement. For both of the airspeed and angle of attack datums given above, the datum position was limited to $\pm$ 3 inches at the top of the control wheel.

8.4 Control Law Analysis Against the Criteria

The control law characteristics can be seen in the following set of tables 8.1 to 8.10 and in figures 8.7 to 8.10. The control laws here are refined from the control laws described within Chapter 7.The following control laws were used:

Law Reference	Description.
Base	Unaugmented Aircraft.
1	Augmented Angle of Attack.
3	Pitch Rate with trim to Airspeed.
6	Normal Acceleration.
7	Normal Acceleration with trim to Airspeed.
10	Normal Acceleration with trim to Angle of Attack.

Gibson's Attitude Frequency Response Boundaries

The response plots given for these control laws are shown on figure 8.6 and an actuator is included in the response. The actuator is modelled as a first order lag with a 60 ms time constant.

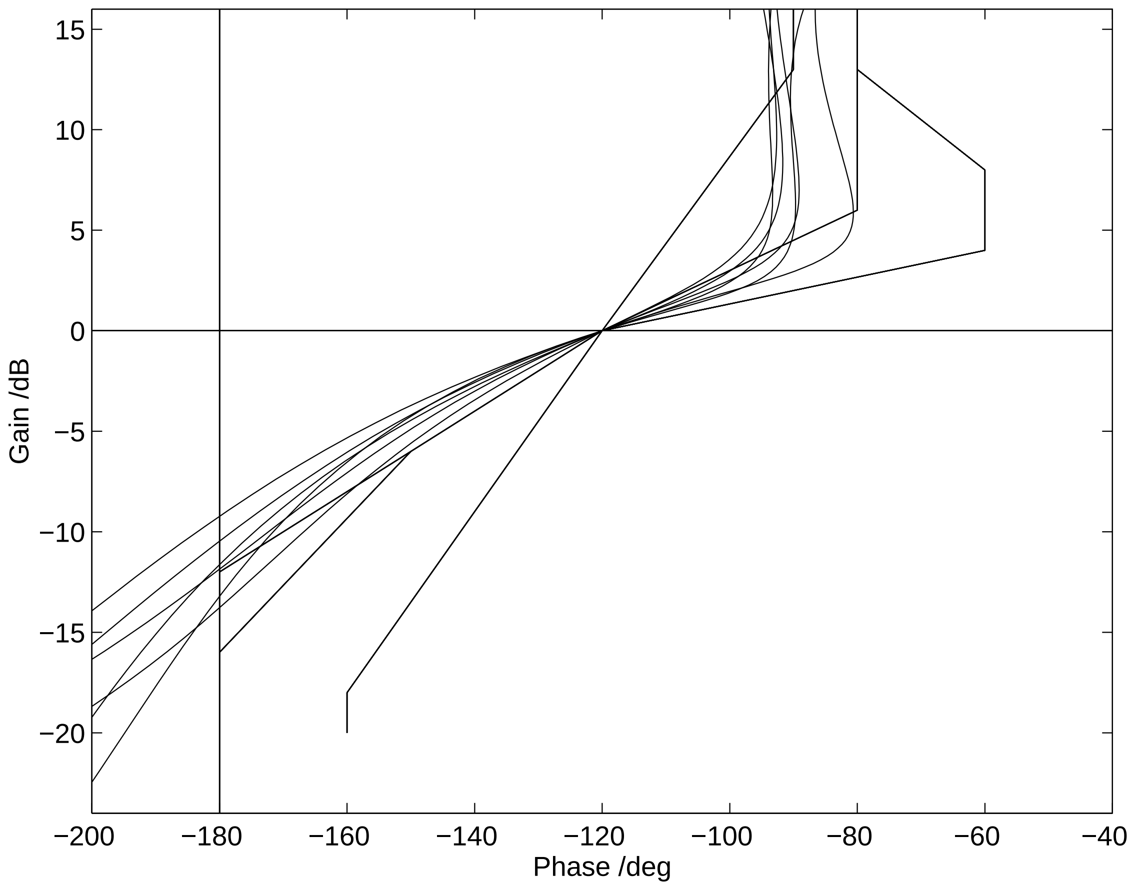


Figure 8.6: Gibson's Criterion - Laws 0, 1 and 10

It can be seen that the response plots lie more or less within the boundaries specified, though there is some difference between the plots at higher frequencies.

Bandwidth

The values for the pitch attitude and flight path bandwidths can be seen in tables 8.1, 8.2 and 8.3, and figures 8.7 and 8.8. It can be seen that all of the augmented configurations have Level 1 bandwidth characteristics, but the unaugmented aircraft is borderline Level 2 / 3.

Law Number	ω_{BW_θ} (rad/s)	$\omega_{BW_{\gamma P}}$ (rad/s)	Phase rate (deg/Hz)	Phase Delay (s)	-180 deg phase Frequency (Hz)
0	0.784	0.456	49.50	0.069	2.56
1	1.866	0.884	48.85	0.068	4.91
3	2.037	0.832	45.25	0.063	4.99
6	1.816	0.858	30.94	0.043	6.32
7	1.852	0.814	33.13	0.046	5.88
10	1.956	0.836	35.51	0.049	5.81

Table 8.1: Bandwidth and Phase Delays - 120 knots, flap 4

Phase Delay

The phase delay characteristics can be seen on tables 8.1, 8.2 and 8.3 and figure 8.9. It can be seen that all of the configurations should not be PIO prone for the short term response characteristics.

Neal-Smith

The Neal-Smith characteristics can be seen in tables 8.6, 8.5 and 8.4, and on figure 8.10 for the landing flight case. It can be seen that all of the resonance values are low, and all of the pilot compensation values are within Level 1 limits except for the unaugmented aircraft, which requires excessive pilot compensation.

Law Number	ω_{BW_θ} (rad/s)	$\omega_{BW_{\gamma P}}$ (rad/s)	Phase rate (deg/Hz)	Phase Delay (s)	-180 deg phase Frequency (Hz)
0	1.027	0.587	45.91	0.064	2.86
1	2.234	1.048	47.61	0.066	5.41
3	2.422	0.890	46.37	0.064	5.53
6	2.076	0.896	30.47	0.042	7.14
7	2.287	0.875	31.42	0.044	7.13
10	2.494	0.962	34.23	0.048	7.02

Table 8.2: Bandwidth and Phase Delays - 140 knots, flap 4

Law Number	ω_{BW_θ} (rad/s)	$\omega_{BW_{\gamma P}}$ (rad/s)	Phase rate (deg/Hz)	Phase Delay (s)	-180 deg phase Frequency (Hz)
0	1.427	0.800	47.56	0.066	3.48
1	3.006	1.325	47.92	0.067	6.49
3	3.217	1.043	53.44	0.074	6.46
6	1.847	0.828	57.81	0.080	4.09
7	3.436	0.997	30.09	0.042	10.82
10	3.879	1.237	32.59	0.045	10.29

Table 8.3: Bandwidth and Phase Delays - 200 knots, flap 0

	200 knots, flap 0, with actuator		200 knots, flap 0, no actuator	
	NS compensation (deg)	NS resonance	NS compensation (deg)	NS resonance
0	17.3 lead	-1.81 dB	11.44 lead	-1.88 dB
1	21.68 lag	-3.00 dB	22.79 lag	-3.00 dB
3	13.32 lag	-3.00 dB	13.62 lag	-3.00 dB
6	4.83 lag	-2.96 dB	4.90 lead	-2.99 dB
7	11.32 lag	-3.00 dB	11.42 lag	-3.00 dB
10	17.87 lag	-3.00 dB	17.97 lag	-3.00 dB

Table 8.4: Neal-Smith Compensation and Resonance Values for 200 knots, flap 0

	140 knots, flap 4, with actuator		140 knots, flap 4, no actuator	
	NS compensation (deg)	NS resonance	NS compensation (deg)	NS resonance
0	72.31 lead	-2.94 dB	62.85 lead	-3.00 dB
1	12.38 lag	-2.72 dB	13.01 lag	-2.95 dB
3	8.882 lag	-3.00 dB	9.117 lag	-3.00 dB
6	3.949 lag	-2.38 dB	3.807 lag	-2.53 dB
7	5.379 lag	-3.00 dB	5.475 lag	-3.00 dB
10	10.46 lag	-3.00 dB	10.66 lag	-3.00 dB

Table 8.5: Neal-Smith Compensation and Resonance Values for 140 knots, flap 4

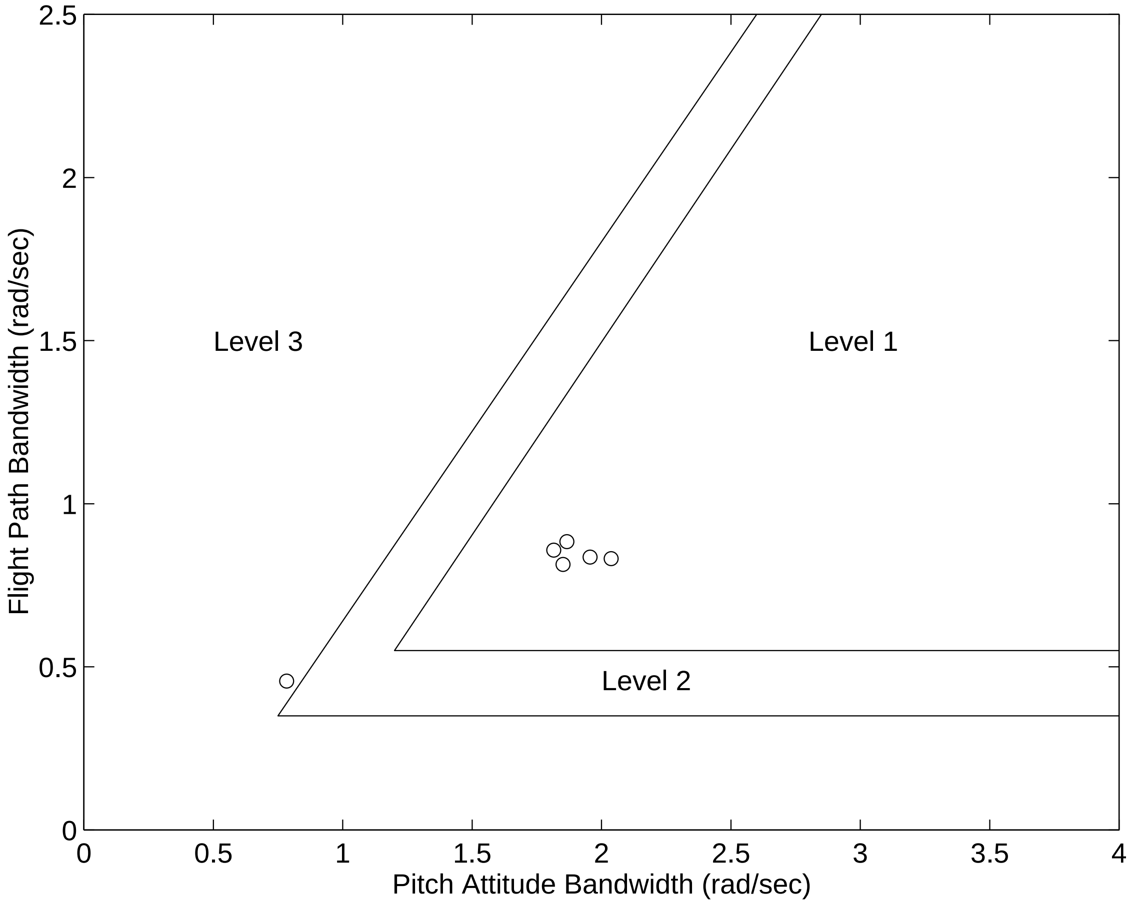


Figure 8.7: Pitch Attitude Bandwidth Versus Flight Path Bandwidth for the Landing Flight Case (120 knots, flap 4)

CAP and GCAP

From table 8.7, it can be seen that all of the augmented control laws have approximately similar values of GCAP, although the CAP values do not correspond to the GCAP values for some of the different control laws.

It is also interesting to note that when actuator dynamics are included in the GCAP calculation, the results no longer are comparable with the CAP calculation. This is especially visible with the baseline law and law 1 which have angle of attack response characteristics.

Gibson's Dropback Criterion

Gibson's dropback results may be seen in figure 8.11 and table 8.8. As before there are some variations in the dropback parameter even though all of the laws were designed to the desired level of dropback due to the effects of the trimming to angle

	120 knots, flap 4, with actuator		120 knots, flap 4, no actuator	
	NS compensation (deg)	NS resonance	NS compensation (deg)	NS resonance
0	114.4 lead	-3.00 dB	98.84 lead	-3.00 dB
1	2.275 lag	-2.07 dB	2.788 lag	-2.48 dB
3	2.618 lag	-2.88 dB	2.537 lag	-3.00 dB
6	0.968 lag	-1.29 dB	0.655 lag	-1.58 dB
7	2.276 lead	-2.53 dB	2.998 lead	-2.75 dB
10	1.234 lag	-2.57 dB	1.064 lag	-2.79 dB

Table 8.6: Neal-Smith Compensation and Resonance Values for 120 knots, flap 4

	200 knots, flap 0		140 knots, flap 4		120 knots, flap 4	
	CAP	GCAP	CAP	GCAP	CAP	GCAP
0	0.196	0.197	0.210	0.212	0.188	0.190
1	0.664	0.586	0.691	0.666	0.665	0.648
3	0.997	0.489	1.000	0.609	0.965	0.639
6	0.411	0.208	0.448	0.620	0.453	0.674
7	0.810	0.679	0.748	0.667	0.690	0.647
10	0.929	0.806	0.846	0.738	0.757	0.673

Table 8.7: CAP and GCAP Values for the Landing Flight Case (120 knots, flap 4)

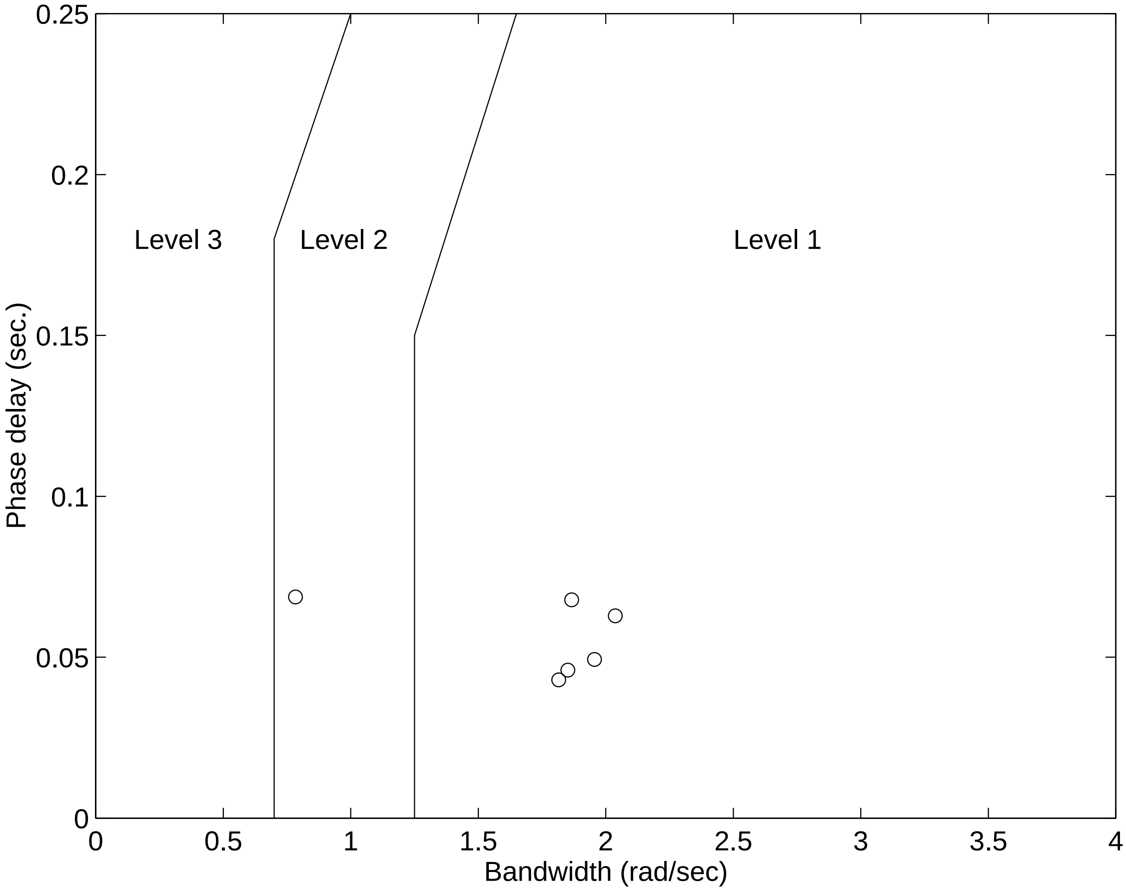


Figure 8.8: Pitch Attitude Bandwidth Versus Phase Delay for the Landing Flight Case (120 knots, flap 4)

of attack or airspeed. All of the control laws here were designed using the dropback definition given in section 4.4.

It can be also seen that the q_{max}/q_{ss} values are all around 1.5 except for law 1.

Short Term Mode Characteristics

From table 8.9, it can be seen that all of the short term mode damping ratios are approximately 0.7, but there is some variation in the short term mode natural frequencies to account for the requirement to design for a constant GCAP value.

Long Term Mode Characteristics

From table 8.10, it can be seen that the long term characteristics of the modes with static stability (whether through angle of attack or airspeed reference) are essentially of similar orders of magnitude. However, the damping ratios of the pitch rate laws are generally higher than those of the normal acceleration laws. This may

Law	Dropback	q_{max}/q_{ss}
Base	0.6673	1.5442
1	2.2096	2.1712
3	0.6804	1.5679
6	0.6848	1.5208
7	0.8161	1.5665
10	0.5550	1.4836

Table 8.8: Dropback and q_{max}/q_{ss} Values for the Landing Flight Case (120 knots, flap 4)

	200 knots, flap 0		140 knots, flap 4		120 knots, flap 4	
	ω_{st} (rad/s)	ζ_{st}	ω_{st} (rad/s)	ζ_{st}	ω_{st} (rad/s)	ζ_{st}
0	1.31	0.54	0.94	0.55	0.75	0.61
1	0.71	2.41	1.71	0.69	1.40	0.70
3	2.95	0.68	2.05	0.70	1.69	0.69
6	1.89	0.71	1.37	0.73	1.16	0.71
7	2.66	0.70	1.77	0.71	1.43	0.69
10	2.85	0.69	1.89	0.70	1.50	0.69

Table 8.9: Longitudinal Short Term Mode Characteristics

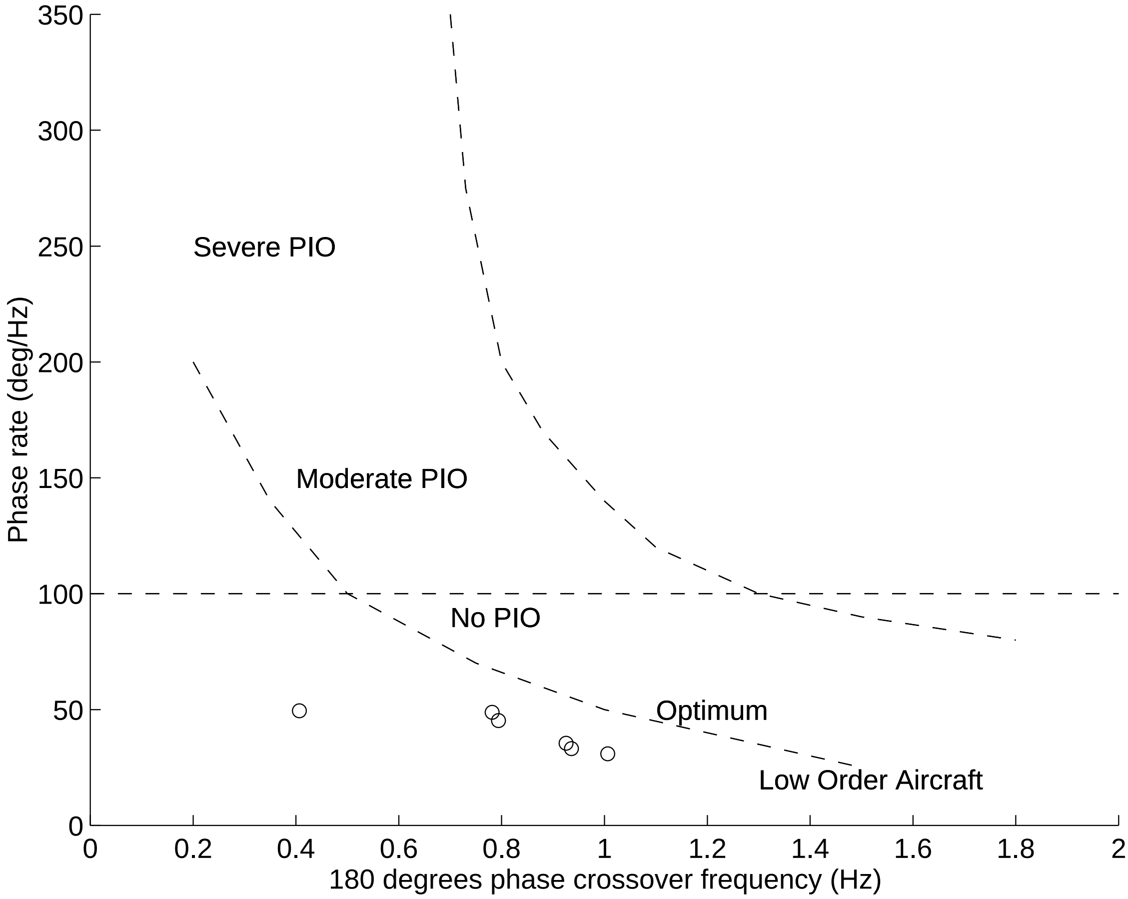


Figure 8.9: Phase Rate Versus Minimum Phase Crossover Frequency for the Landing Flight Case (120 knots, flap 4)

be addressed if required through additional pitch attitude feedback.

Sturmer's Pitch Sensitivity Criterion

The results from Sturmer's pitch sensitivity criterion can be seen on figure 8.12. It may be seen that all of the configurations lie in the desired region, except for the baseline aircraft, which is the single line at the top of the plot. All of the configurations here have an identical initial pitch acceleration of 0.6 deg/s^2 per lb stick force.

8.5 Flying Qualities Experiment Results

This section contains the results for each of the configurations flown during the evaluations. The results were recorded using the comment cards which can be found

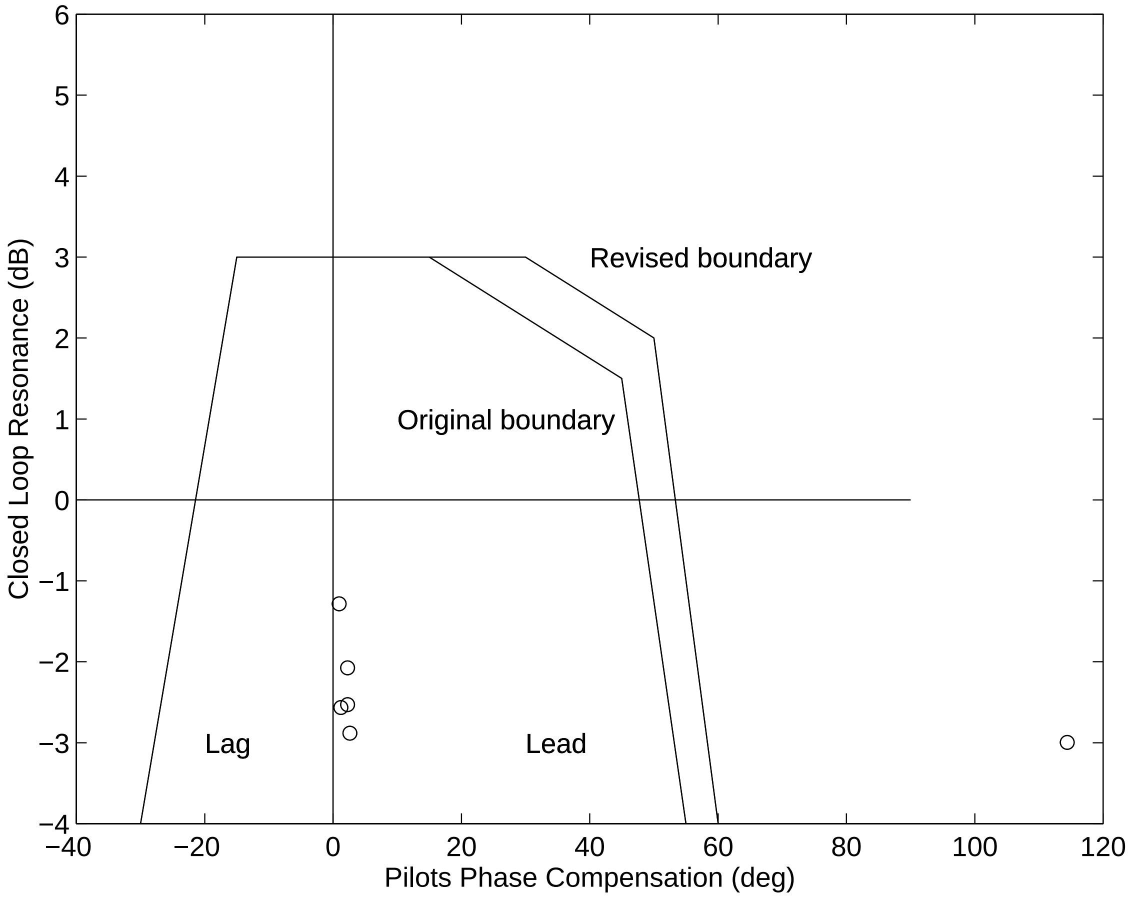


Figure 8.10: Neal-Smith Characteristics for the Landing Flight Case (120 knots, flap 4)

in section D.1.

8.5.1 Evaluation Pilots

Two pilots took part in these evaluations. The first is Pilot A whose biography is in section 7.5.1. The second is an experienced civil flying instructor, with some, although limited large aircraft experience.

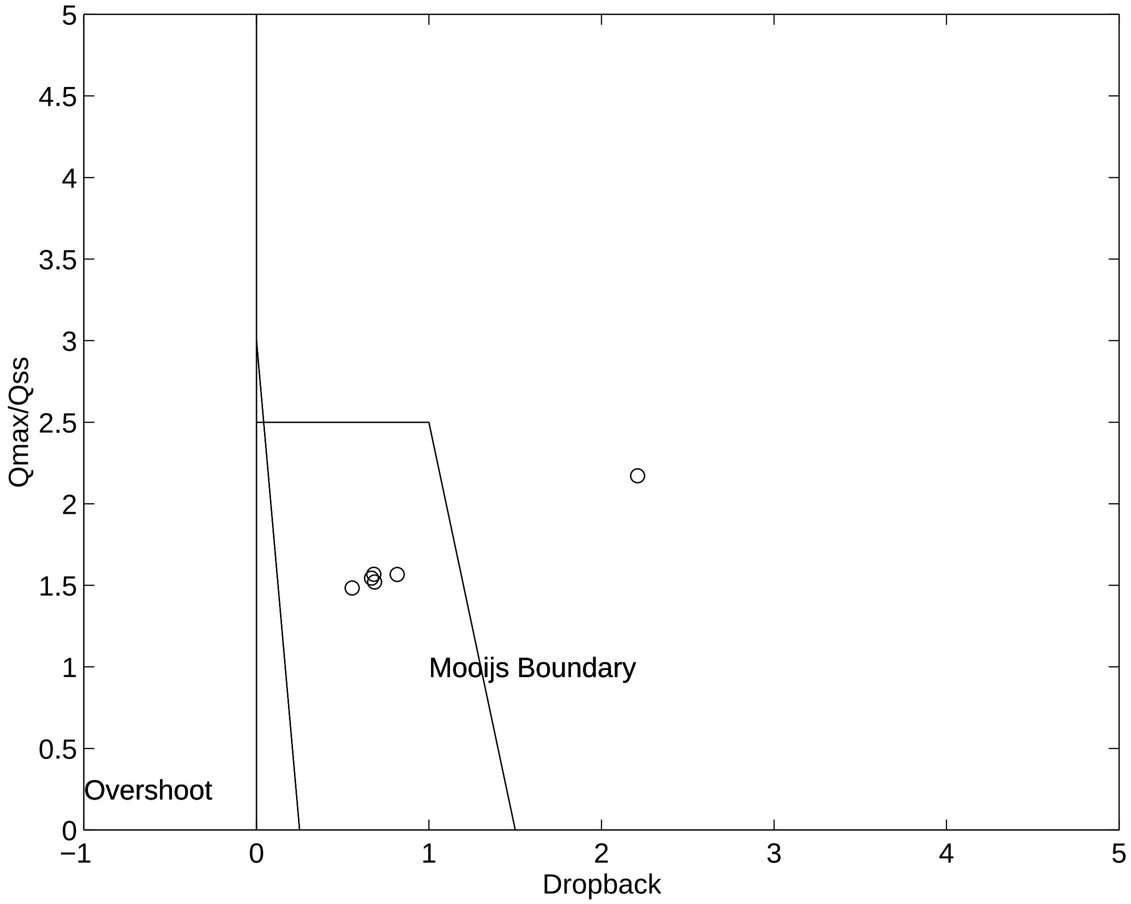


Figure 8.11: Gibson's Dropback Results for the Landing Flight Case (120 knots, flap 4)

Pilot E - Gary Giles

He has accumulated nearly 1400 hours, much of it instructing on light aircraft. In addition, he has flown a number of twin aircraft. He is a BX rated CAA examiner, and is authorised to carry out flight tests. He now flies Slingsby Fireflies for Hunting Aviation at RAF Barkston Heath.

8.5.2 Evaluation Summary

In total, 2 pilots made 31 approaches during at total of 2 evaluations with 11 different control law configurations, plus a number of approaches to a simulated tanker aircraft. Both pilots had a single evaluation session each. Table 8.11 gives a summary of these results.

	200 knots, flap 0			140 knots, flap 4			120 knots, flap 4		
	ζ_{lt}	ω_{lt} (rad/s)	T_{lt} (s)	ζ_{lt}	ω_{lt} (rad/s)	T_{lt} (s)	ζ_{lt}	ω_{lt} (rad/s)	T_{lt} (s)
0	0.08	0.29	78.8	0.09	0.14	68.3	0.15	0.05	41.5
1	0.09	0.24	67.4	0.15	0.20	42.4	0.17	0.16	37.3
3	0.11	0.21	55.7	0.13	0.27	47.2	0.14	0.33	43.6
7	0.10	0.18	62.1	0.12	0.16	52.8	0.13	0.17	49.8
10	0.09	0.22	68.7	0.11	0.15	54.8	0.13	0.13	49.9

Table 8.10: Longitudinal Long Term Mode Characteristics

Pilot	Configurations	Evaluations	Approaches
A	6	13	15
E	6	12	16
Total	12	25	31

Table 8.11: Evaluation Summary

The evaluations were performed on the following dates

Session Number	Date
A-3	16th January 1997.
E-1	18th February 1997.

In addition, a calibration session was carried out by the author in January 1997 to check the simulator performance and the control laws were performing as designed. No modifications were made after that session. No problems were experienced with simulator performance during the evaluations, although the lack of visual and motion cues again resulted in many of the landings being excessively firm.

8.5.3 Control Law Characteristics

This section summarises the flying qualities of each of the configurations flown, i.e. the baseline aircraft plus 5 control laws.

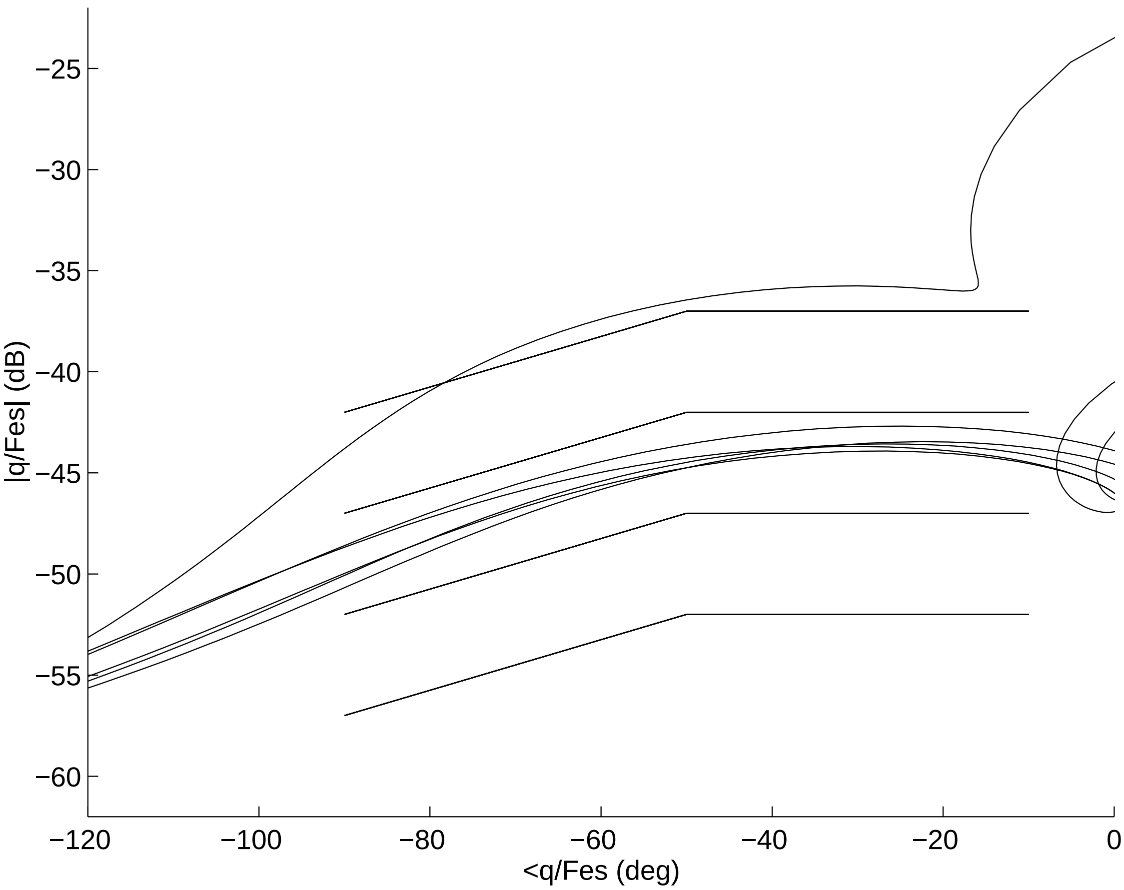


Figure 8.12: Sturmer's Pitch Sensitivity Criterion (120 knots, flap 4)

Basic Aircraft

For the formation task, the baseline aircraft was found to be sluggish with the pilot having to apply a large amount of compensation to achieve the desired corrections. There was also a tendency for the pilot to overcontrol, with a longitudinal oscillation, which was not a PIO, but the pilot found it difficult to stabilise the configuration.

For the windshear approach task, this law was best described as sluggish, though it was conventional in nature. There was also a slight problem in the flare as the pilot was having problems stabilising the configuration and the control of the touchdown parameters was not good. The most objectionable feature of this configuration was the 'looseness' in pitch.

Augmented Angle of Attack (Law 1)

For the formation task, this law was better than the baseline aircraft, though there were pitching effects with power which made the initial acquisition of the target a little more difficult than with the other laws. Moderate compensation was required to achieve the desired compensation.

For the windshear approach task, this was very much a 'middle of the road' configuration which had reasonable characteristics, but was not spectacular. It did not receive as high CHRs as some of the later laws tested.

Pitch Rate with Trim to Airspeed (Law 3)

This configuration was one of the better configurations for the formation task. The pilot found that he was generally more successful than before with no particular problems.

For the windshear approach task, this law performed reasonably well with conventional characteristics although the pilot preferred law 10 for this particular task.

Normal Acceleration (Law 6)

For the formation task, the pilot again found this configuration quite difficult to stabilise. He could achieve desired corrections, but with difficulty and there was a slight tendency to overcontrol. The configuration was described as adequate though the pilot was able to recover from a bad situation more easily than with the baseline aircraft.

For the windshear approach task, the pilot liked the flight path stability, giving him more time for airspeed control. The windshear task was a non-event, requiring solely a power increase which was easily managed. The flare was surprisingly conventional and this received the best CHRs for the approach task.

Normal Acceleration with Trim to Airspeed (Law 7)

This control law was one of the best laws for the formation flying task. It had very nice longitudinal characteristics and the pilot generally found it reasonably easy to achieve the desired level of performance.

For the windshear approach task, this law was another with reasonable, if not sparkling performance. The flight path stability was nice, though not as good as law 6 and the pilot was not aware of any significant ability to control airspeed over law 6. The trimming characteristics were satisfactory, though there was a slight tendency to float in the flare, which was the most objectionable feature of this configuration.

Normal Acceleration with Trim to Angle of Attack (Law 10)

This was an acceptable law, but required more compensation than law 7 to achieve the desired level of performance. However, it tended to wander off a little more than law 7 when the stick was released and the pilot found it more difficult to back out of the control loop than he did with law 7.

For the windshear approach task, this aircraft has conventional characteristics and the pilot found it relatively easy to control the flight path. It also had conventional flare characteristics and desirable longitudinal control forces.

8.6 Discussion

This section contains the discussion of the results. It has been divided into discussion concerning the control laws themselves, and how they correspond to the criteria. Each task is also discussed independently.

8.6.1 Approach Task

As a result of the previous evaluations, some initial control law 'filtering' had already been carried out to remove control law types which would not be appropriate. As a result of this, the remaining laws were known to be suitable for the approach task. Therefore the effects of windshear were to be assessed for these known laws.

Response Characteristics

No problems were experienced with the response characteristics in terms of abruptness or sluggishness. Using the 'Constant CAP' design approach, the initial responses of all of the laws was neither abrupt nor sluggish. This confirms the results of the previous evaluations, especially since most of the laws were redesigned, resulting in a 'short term mode frequency extension' capability, i.e. the laws all had a constant CAP value but an increased short term mode natural frequency. In addition, all of the laws were designed to specified dropback values (either positive or zero) which was another contributory factor. Laws with overshoot (i.e. negative dropback) have been found to be slightly sluggish [62].

Furthermore, none of the augmented configurations had a problem with the flight path / pitch attitude consonance, suggesting good flight path dynamics and a suitable CAP / dropback combination. As previously shown in reference [58], increasing the dropback must reduce the flight path time delay.

It was found that for the approach task, the GCAP criterion could be used to effectively design the short term dynamics of the aircraft. By using a constant GCAP value, no problems were found with the control laws in terms of abruptness or sluggishness which would indicate that the characteristics of the short term mode are suitable. In addition, it was found that this GCAP value could be disconnected from the short term mode natural frequency so that improvements in short term mode natural frequency could be obtained but with still an 'optimum' GCAP value.

It is also necessary to control the dropback values for the pitch attitude response since they also contribute to the pilot's impression of the control laws.

A constant initial pitch acceleration per unit stick force across the flight envelope / airspeed range gave acceptable control forces across the envelope, though this is probably also dependent on the effective GCAP value. Analysis of an existing q-pot system tends to give a constant value of the initial pitch acceleration per unit stick force.

Trim Characteristics

The trim characteristics were generally found to be desirable. One pilot liked the positive movement of the control wheel with trimming at low speed for the normal acceleration with trim to angle of attack law. However, comments may have indicated that this law may have had too much wheel movement, resulting in quite a far aft position at low airspeeds. This requires further investigation. Additional pilot comments also indicated that wheel datum movement may only be desirable at low airspeeds, and the rear control wheel position indicates that the pilot is at a low airspeed. Again, this requires further investigation.

Pilot comments indicated that trimming was desirable from an airspeed awareness point-of-view for the approach and landing task from the results in Chapter 7. However, for the windshear approach, the best performance was obtained from the non-speed stable law, since the aircraft did not pitch down in response to the airspeed change. For the pre-windshear segment of the approach, the non-speed stable normal acceleration law and the trim to airspeed normal acceleration law received the best Cooper Harper Ratings from both pilots. This was due to the flight path angle hold characteristics of the laws combined with the trim to airspeed characteristic of the normal acceleration law.

However, comments from the previous evaluations indicate that a pure normal acceleration law gives better performance when flown with an autothrottle, since the airspeed is 'dialled-in' on the autothrottle control panel, and a non-speed stable law will not require any subsequent pilot trimming action as the airspeed changes. Most of the pilots from the last evaluations liked this feature.

Therefore, this work so far has shown that an aircraft can be designed with trim to airspeed or trim to angle of attack control laws, but this static stability is not necessary for good flying and handling qualities. Comments from the non-test pilot, from this set of evaluations indicated that trimming does not necessarily improve a pilot's airspeed awareness, and is a task which requires some pilot attention that could more usefully be implemented in other ways. In addition, trimming becomes a subconscious act, and if the pilot is therefore removing any out-of-trim forces, he may not be consciously aware if he is off the trim speed, or he may not even be aware of what the trim airspeed is. These remarks are important since it is this type of pilot who will be flying and operating this aircraft on a daily basis.

In addition, autothrottles are becoming more and more widely used in general line operations - the Airbus A320 is rarely flown without the autothrottle engaged. If a non-speed stable law is optimal for an aircraft flown in autothrottle, then this should be implemented. From the previous evaluations, the best rating was for a pure normal acceleration law flown with autothrottle engaged. This rating came from an experienced military and civil test pilot, who had flown a wide variety of different laws, and had participated in a number of display and control law trials. His comments indicated the pure normal acceleration / autothrottle combination was almost perfect, and the configuration only lacked a flight path vector display.

The Effect of Windshear

The windshear penetration gave some interesting results. The control law which gave the best ratings for the windshear penetration was the normal acceleration law with no static stability. This was due to the fact that the aircraft did not have a tendency to pitch as the airspeed changed, and therefore the pilot had more time for airspeed control. If an autothrottle had been fitted, the difference to the airspeed stable laws may not have been quite so large since the autothrottle would reduce the airspeed transients. The normal acceleration control law received the best ratings from the majority of the pilots when flown during the previous set of evaluations, due to the maintenance of flight path during an airspeed change. It has been said that trimming can improve the airspeed awareness, but although these evaluations have shown through pilot comments that there is a benefit present, the magnitude of the benefit may be surprisingly small.

Control Forces

The control forces were considered appropriate for all of the laws tried. Again, all of the laws were designed to a constant value of GCAP and a constant initial pitch acceleration per unit wheel force. This gave effectively a constant stick force per g value for each law, of approximately 60 lb/g at approach airspeeds. The initial pitch acceleration was kept constant as the airspeed increased, and therefore the stick force per g changed as the GCAP value changed with airspeed. No unfavourable comments were received concerning the stick forces at the higher airspeeds tested, and at the airspeeds used for the formation flying task, the stick force per g would still be around 60 lb/g.

Flare Characteristics

Some modifications were made to the flare law from the results of the Chapter 7 evaluations. For the pure normal acceleration law, the stick force required to maintain a constant pitch attitude in the flare was increased from 60 to 100 lb/rad. In other words, the pilot was required to hold a force of 10 lbs to maintain a pitch attitude of 5.7 degrees greater than that of the reference attitude [58]. This gave much more desirable characteristics, as comments from the previous evaluations indicated that the stick forces were a little light. The comments obtained for the modified flare law used for these evaluations included ‘surprisingly conventional’.

However, for the airspeed stable laws, the effective forces in the flare were reduced due to the fact that the stick force required to hold an off-trim airspeed was reduced (from around 3 knots/lb to 4 knots/lb). Therefore, the forces in the flare were lighter. Pilot comment indicates that heavier forces are more desirable, and therefore for these trim to speed laws, an additional flare law would be required to increase the forces in the flare, if the desirably low levels of stick force per knot are used.

For law 10 (normal acceleration with trim to angle of attack), the control forces were deemed to be appropriate in the flare. Finally, for the augmented aircraft law, where the control wheel is still connected directly to the elevator, the control forces were also deemed to be appropriate.

Displays

A flight path vector display was used with the evaluations. Due to hardware limitations, the flight director bars were programmed so that they crossed the artificial horizon pitch attitude ladder at the effective flight path angle. The pilots found that they were very useful, and despite the implementation, which sometimes lead to the pilot interpreting the bars as an actual flight director, the pilot’s found that they were using them more and more. However, comments like ‘I’m using it more and more, and it’s disappointing me’ were found, and further investigation revealed that the display warranted improvement through some form of quickening / prediction.

The airspeed trend vector display was found to be useful, and as with previous evaluations [4, 58], it made the airspeed tape display workable, and assisted with the airspeed control task through giving the pilot predicted information.

Lateral / Directional Control Laws

For the approach and landing task, the lateral / directional control laws were not a factor. This is unsurprising since they had been tried and tested previously, and were found to be suitable. In addition, the task was specifically designed so that only the longitudinal dynamics would be excited.

8.6.2 Formation Task

The formation task gave some interesting results. It turned out to be a tight flight path control task, with (unsurprisingly) very little head down time.

Longitudinal Control

With the formation task, a suitable GCAP value was not available and therefore different values were tried. The target short term mode natural frequency was selected for each law based on experience, and also an attempt to maintain constant control law gain values was made.

The two laws which received the best rating were those where the law met Gibson's criterion (see section 4.6). In addition, these two laws had the greatest GCAP values. However, one law which was not rated so well had a GCAP value comparable with the value from these laws. Therefore it would seem that GCAP may be a factor, but Gibson's criterion almost certainly is a criterion. This would require further investigation to confirm, but designing a law which meets Gibson's criterion, and also has a reasonably high GCAP value (around 0.5 compared to the value of approximately 0.6 used for the approach) should produce a reasonable control law.

Lateral / Directional Control Laws

The same lateral control law was used for each of the individual longitudinal control laws, and therefore should have been a constant factor in the evaluations. Looking at the Cranfield Handling Qualities Rating scale for the formation task D.10 showed that all of the directional ratings were 2, and all of the lateral ratings were 3, with the exception of law 0 (the unaugmented aircraft), which had a lateral rating of 4. This was probably due to the excessive workload experienced in the longitudinal task with the unaugmented aircraft, hence resulting in a deterioration in the lateral control task. These ratings may be considered to be identical to Cooper Harper ratings for the purpose of this report.

Airspeed Control

Comments from the previous evaluations indicated that the gearing between the throttle position and engine response was too high, meaning that the pilot could not control the thrust as precisely as with some engines. This therefore gave some problems in the formation task. The solution was to use the airbrake. This was modelled as a pure drag brake, i.e. there was no pitching moment.

Stick Forces

No comments were made concerning the wheel forces. However, the task was not aggressive enough to excite any large pitch forces. The pilot was briefed to acquire the tanker as quickly as possible, which required an increase in airspeed, and a climb, and no adverse comments were received concerning wheel force during this phase. All of the control laws were designed to have a constant initial pitch acceleration per unit stick force across the whole of the airspeed range, and this chosen value was the same for each individual law.

Trimming

The trim was only really used with the unaugmented configuration, and to a very limited extent, the augmented aircraft law. Both of these are laws where the control wheel is connected directly to the elevators. None of the augmented configurations warranted trimming, which is understandable since the task is flown at a constant airspeed.

8.6.3 Comparison Against the Criteria

The configurations considered were compared to the criteria previously considered. The best control laws met all of the criteria proposed. However, some initial sorting of the criteria which have been proposed was initially performed to determine which were relevant.

It was generally found that most of the limits placed on the criteria were too lax, compared to the results of these evaluations. Gibson's criteria are the exception to this - they seem to have sufficiently tight boundaries that they can be used for design purposes. This is also true for the CAP criterion. Other criteria, such as the Bandwidth criterion and Neal-Smith seem to have quite relaxed boundaries, and therefore cannot be used specifically as design criteria. However, poor performance results if the control laws do not meet these boundaries, and therefore they are useful as a check that the proposed law is within limits.

8.7 Summary Conclusions

- Good pitch dynamics give the pilot more time for airspeed control;
- For the windshear penetration task, the 'pure' normal acceleration law gives the best performance;
- The pilot is sensitive (in classical terms) to manoeuvre margin, and not to static margin, although he is aware of the presence of static margin;
- For the formation task, no benefit was found from having to trim to airspeed or angle of attack;
- The benefit of trimming for the approach and landing task to improve airspeed awareness is questionable, especially with the benefits found with non airspeed stable laws during windshear.

9 Summary Discussions

This Chapter ties-in the results of the preceding Chapters. The discussion contained within this Chapter mainly relates to the work described previously within Chapters 3 to 8, but the key points from Chapter 2 are also included.

9.1 Desirable Control Law Response Characteristics

These studies have shown that there are advantages when using control laws with unconventional response characteristics such as a normal acceleration response characteristic for the approach flying qualities task considered here. The normal acceleration characteristics give good flight path stability and reduce the pilot's workload significantly as they enable the pilot to adopt an open loop strategy for flight path control situations such as the ILS approach task.

Previously, doubts have been raised over the ability of the pilot to adopt a tight, closed loop control strategy with anything other than a classical response characteristic. Doubts have been raised concerning the ability of some of these laws to perform these tight tasks [4]. The work performed here demonstrates that unconventional control law response characteristics such as the normal acceleration law may be used for a tight closed loop task such as air-to-air refuelling.

For the formation flying task, a closed loop task, the usefulness of selecting the correct flying qualities criteria for design purposes became clear. Since the design criteria were chosen carefully, the control laws which met the criteria produced acceptable aircraft, irrespective of the specific response type. For the more open loop approach task, the control law response type became more important, as described above. The main improvements to the flying qualities of the basic aircraft came through improving the pitch damping of the aircraft and quickening the response by increasing the CAP parameter. The final small improvement came from the response type itself.

During both sets of evaluations, it also became clear that pilots expect the aircraft to respond in a certain manner, based on their previous flying experience. Of the two sets of evaluations shown here, the results from the first evaluations showed that the pilots were generally expecting a classical aircraft. However, after some acclimatisation, the results from the second evaluations showed that the evaluation pilots became more open minded concerning unconventional aircraft as they grew used to them. Informal pilot comment confirmed this strongly, with pilots becoming more in favour of the unconventional control law response types as they flew them for longer periods.

9.2 Flying Qualities Design Criteria Discussion

Much use has been made of the CAP criteria and its derivative, Generic CAP. These have proven to be suitable for use with transport aircraft as both design and evaluation criteria, and they have also proven to be suitable for both conventional and non-conventional response characteristics.

The dropback criterion has also been used as a design criterion since it is possible to neglect the pitch attitude dropback when designing the different control laws, giving an aircraft with a pitch attitude response with either overshoot or dropback.

Phase rate proved to be a useful criterion since it is the sole criterion considered here which is sensitive to the effects of time delay. Phase rate is only applicable to aircraft where the pitch attitude phase angle decreases below -180 degrees, i.e. an augmented aircraft.

Neal-Smith showed some promising trends, but problems were experienced in its use since it does require a pilot model to be used. In addition, there is still some doubt concerning the values of the pilot time delay and bandwidth.

The bandwidth criteria proved to be useful in that there is a requirement for a minimum bandwidth in pitch attitude. It was generally found that, if the desired GCAP value was obtained with a suitable dropback value, then the pitch attitude bandwidth would also be suitable. Hence it is not so much a design requirement as a design consideration. Work exists which demonstrates that there may be an upper limit to permissible bandwidth [4]. In addition, the bandwidth boundaries used within this thesis seem appropriate, though the number of datapoints is obviously small.

The initial pitch acceleration was used to determine the control forces. This seems to be appropriate in light of pilot comments which stated that there were no unsuitable aircraft. This ties in with Sturmer's pitch sensitivity criterion for classical aircraft, which exists as a pitch rate sensitivity measure. Further analysis of Sturmer's criterion does shows that this criterion is also sensitive to stick force per unit normal acceleration.

The results found here give the same trends as when the data from past flying qualities research programmes is analysed with respect to these criteria. Therefore it would seem that the past research programmes can provide a useful source of data and it is the methods which have been used to analyse it which have not been as thorough as they may have been. The selection of desirable values for the GCAP and dropback parameters are two examples of this.

Finally, the use of GCAP may be more suitable than using CAP in combination with

LOES since GCAP does not suffer from some of the drawbacks that can be common when using the LOES matching process, such as the problem which is caused if a poor LOES match is obtained.

9.3 Law Independent Design Criteria

The use of law independent design criteria for flight control laws was demonstrated in this thesis. It has been demonstrated that these criteria may be successfully used and applied to any control law with rate-like characteristics. The only differences between the control laws designed to these criteria were due to the individual characteristics to the particular control law concept, such as flight path angle hold for a normal acceleration law compared to a pitch attitude hold for a pitch rate demand law. The most suitable control law type depends on the task which the law is required to perform.

Since these criteria are suitable for all generic rate demand laws tested, it seems sensible that they should be considered as the foundation of a certification requirement for aircraft with unconventional flying qualities.

9.4 Trimming Issues

Some of the aircraft flown for these evaluations did not require trimming, and others required trimming in a slightly non-conventional sense, i.e. trim to airspeed. Initial pilot comments indicated that in order to keep the pilot in the loop, it is necessary to make him do something. This is in-line with what a pilot would do in a classical aircraft.

Therefore for a civil aircraft, it was initially thought that an airspeed trimming strategy should be desirable, and this was confirmed very strongly by one pilot, especially due to the airspeed reference bug which was used to highlight the current airspeed reference. However, with subsequent evaluations, the pilots became used to the lack of trimming, and stated that they preferred the lower workload due to removing the requirement to trim.

It must be considered that when trimming is removed, some form of envelope protection becomes more desirable as there may be less cues to the pilot that he is reaching the edge of the flight envelope. This should form a key part of the system design. In addition, the use of the autothrottle becomes a more important part of the design since comments indicated that pilots preferred the aircraft when the autothrottle was selected, and trimming was less desirable than not trimming when the autothrottle was selected.

The results of the first two sets of approach tasks indicate that in classical terms, the pilot is sensitive to manoeuvre margin, and this makes a suitable design parameter through the use of the GCAP criterion. These evaluations demonstrated that the pilot is sensitive to static margin, primarily through the requirement to trim, but aircraft with zero static stability do not seem to be penalised by this as long as the short term response (i.e. effective manoeuvre margin) is appropriate. The ability to disconnect the apparent static margin from the apparent manoeuvre margin is something which is very difficult in a classical aircraft, but which may be accomplished quite effectively with the use of augmentation or a fly-by-wire system.

9.5 Cockpit Display Design

The displays should be consistent with the command principle in use. The display used for the evaluation is an EFIS display, with an airspeed tape on the left hand side, and a conventional single pointer aircraft altimeter on the right hand side of the primary display.

Several of the pilots commented on the desirability of a flight path vector, especially for the normal acceleration command systems since this is the parameter which they are ultimately trying to control. However, as mentioned before, this type of display suffers since it is necessary to filter the information used to generate the flight path angle as turbulence and other effects can have quite a severe effect. This filtering has the effect of adding lag into the system, which the pilot sees as a time delay. This can have a major effect on the flying qualities, and too great a delay may even make the display a hindrance. The display of flight path angle is possible through the use of head up displays, which are now becoming more common in civil aircraft. However flight path vector and head up displays pose special design problems which need to be successfully overcome in their implementation, such as quickening the flight path vector, and removing turbulence effects from it.

As a general rule, the evaluation pilots liked to be able to observe what they were controlling directly. For the control laws with pitch rate-like characteristics, the pitch attitude is directly observable from either the ‘real world’ horizon or the aircraft attitude indicator. The comments concerning flight path came especially during the normal acceleration type law evaluations, and for these, some form of flight path vector display, which would actually give the aircraft’s current flight path vector, as used on the A320, would have been appropriate.

The airspeed trend vector proved to be useful throughout the evaluations. With the airspeed tape display, it was used in lieu of the trend indications from a conventional airspeed indicator. This was also seen with the previous programme [4], where a similar effect was observed.

One design goal should be to keep the pilot ‘head up and eyeballs out’ for as much time as possible. This ensures that he can keep a good look out for conflicting traffic in the currently congested airspace. As a result of this he can always observe the pitch attitude, even if the real world horizon is not as clear as it might be. However, for a system where the pilot is primarily controlling flight path, the flight path is not directly visible to the pilot, which would necessitate some form of Head Up Display if he is to be able to observe it.

9.6 Airworthiness Requirements

It can be seen that the military airworthiness requirements which are considered as a part of this work are generally based around the CAP requirement, or manoeuvre margin, and this is considered to be suitable in the light of the work carried out here, although only MIL-STD-1797a is applicable to aircraft with non-conventional response types.

The civil airworthiness requirements, which are based around static margin, or static stability are acceptable for classical civil aircraft, but are not suitable for modern augmented fly-by-wire aircraft. This work has shown that effective manoeuvre margin determines flying qualities more than the effective static margin, and the flying qualities requirements should address this. It is suspected that the civil airworthiness requirements have been based around static margin since it is relatively easy to measure through the aircraft’s airspeed characteristics and for classical aircraft, static margin and manoeuvre margin are closely related.

It must also be borne in mind that some modern civil aircraft such as the Airbus A320 do not have a static margin since it does not return to a trimmed angle of attack when disturbed from equilibrium. Therefore, in light of this work, the civil requirements are in need of revision to reflect the changes in the nature of aircraft response and stability characteristics.

A proposed civil flying qualities requirement is not proposed here. However, a requirement along the lines of a modified military flying qualities requirement, i.e. being modelled around GCAP should be suitable. The military requirements should also be modified to reflect the suitability of the Generic CAP methodology to unconventional response characteristics.

9.7 Accomplishment of Objectives

This section considers the objectives and whether they were met.

1. *To further the work of Field, whose work precedes this.* This work does expand on Field's work, by examining and expanding on his results;

2. *To produce a set of flying qualities design requirements for transport aircraft primarily for the approach and landing task.* These requirements were produced from the results of the database work and the literature search;

3. *To consider the project management implications of fly-by-wire technology.* The project management implications showed that the certification process is the critical process, and the design requirements must be known beforehand in order to enable the process to be started;

4. *To consider alternative tasks to the Instrument Landing System task normally used for flying qualities assessment.* A windshear approach task and formation flying task were used for the flying qualities assessment and gave useful results;

5. *To consider the suitability of the current flying qualities requirements for transport aircraft.* The current flying qualities requirements were assessed for transport aircraft - the military requirements are basically suitable, but the civil requirements require major updates in light of the work carried out here.

10 Conclusions and Recommendations

10.1 Conclusions

As a result of this work, the idea of using control law independent design criteria has been proposed and formalised, and a new version of the CAP criterion developed and tested. The following detailed conclusions may also be made:

- The use of control laws with non-conventional response characteristic, specifically a normal acceleration response characteristic, gives very desirable flying qualities for the approach and landing task with a reduced workload compared to a classical aircraft, and these control law types may be used in other tasks such as a formation flying task;
- Automation, specifically autothrottles, can have a large influence on the flying qualities of aircraft and must be considered during the design and development process. The normal acceleration response type was particularly suited to the use of an autothrottle;
- The use of control law independent design requirements was proven and provides a good method of designing control laws. The design requirements developed for the approach and landing gave acceptable flying qualities to a wide range of control laws. The requirements specified here also gave good open and closed loop flying qualities, enabling the pilot to adopt either technique;
- There are significant implications to the design process depending whether a fixed base, moving base or in-flight simulator is used. The requirements for each are significantly different, and must be borne in mind. There is a good agreement between the requirements for a fixed base simulator and an in-flight simulator.
- The major improvement to an aircraft with poor flying qualities comes from increasing the pitch damping and pitch stiffness, and is independent of the control law type selected. The final minor improvement comes directly from the control law response type being evaluated;
- The project management issues must be addressed early and require the full support of the company at all levels. Pilot projects to acquire knowledge before a new aircraft is launched are required, and will produce a better aircraft quicker, at a better price and with lower risk. The flying qualities knowledge has been partly acquired through the use of the research presented in this thesis.

10.2 Recommendations

The following recommendations for further work are made:

- The use of Generic CAP should be examined for a wider range of aircraft classes and tasks;
- The comparability of moving base, fixed base and in-flight simulators requires further examination in light of this thesis;
- The airworthiness requirements should be examined in light of this work, especially the civil ones, to make them applicable to unconventional response characteristics;
- The use of alternative inceptors such as sidesticks should be considered, and requirements for their characteristics examined carefully.

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A Project Management Figures

Process Model Documentation

This section documents the process model used for the programme described here. Each task is described, together with the details of the task, and some background behind it. Prior to this stage, there must be some idea of the customer needs, and this should have been identified beforehand. The programme described here assumes that these needs have been positively identified, and the design process is commencing with them in mind.

Airframe Development

Task No.	Title	Length	Start Date	End Date	Predecessors	Comments
4	Initial Configuration Studies	62	01/07/98	31/08/98		Look at the initial configurations. Sit down with the 'wise men' and define the configuration and general systems layout. This stage is traditionally performed by the chief systems engineers alone, based on their own personal knowledge.
5	Define Configuration	1	01/09/98	01/09/98	4	MILESTONE. This is the stage at which the aircraft configuration is defined. At this stage, the basic aircraft configuration is known, as is the generic systems layout. For example, the number of control surfaces is known, along with the appropriate systems driving them.
6	Develop Configuration	669	01/09/98	30/06/00	4	This is the pre-development phase. During this time, the aircraft is developed to the stage where the configuration is well defined, and it should permit a decision to me made concerning whether the aircraft should be launched.
7	Configuration Fixed	1	01/07/00	01/07/00	6	At this point the configuration is termed 'fixed'. In other words, the airframe manufacturer is happy with it, although customer approval still has to be obtained.
8	Verify with Airlines	183	02/07/00	31/12/00	7	This is the verification period. Although the company will have been working with the launch airlines, they will formally confirm with them that the 'fixed' configuration meets their needs, and any minor defects may be rectified at this stage. It is envisaged that major defects will be rectified much earlier than this, since the design will be well advanced at this point.
9	Configuration Frozen	1	01/01/01	01/01/01	8	This is where the instruction to proceed is authorised. The airline has seen the 'fixed' configuration, and is happy with it.

Task No.	Title	Length	Start Date	End Date	Predecessors	Comments
10	20% release	184	01/07/00	31/12/00	6	This is where a 20% drawing release is authorised. The major components will be defined, and the minor components will be well along the way to completion.
11	Long lead items enter production	1095	01/01/01	31/12/03	10	Initial production will start with the long lead items. These items will have been identified during the initial project stages, and constitute part of the '20%' items.
12	80% release	365	01/01/01	31/12/01	10	One year after the 20% items, the 80% items will be completed. This is where the majority of the airframe components will be complete, and it permits the majority of the characteristics of the airframe to be known.
13	100% release	181	01/01/02	30/06/02	12	By this stage, the complete aircraft design should be available. However, minor modifications may be required, and it should be possible to make these minor modifications without risking the rest of the program.
14	Static Tests	366	01/07/02	01/07/03	13	Static tests are scheduled here, and this has been included for completeness.
15	Major manufacture	730	01/07/02	29/06/04	13	This is where the major manufacturing component starts, although minor components together with the long lead items will have been started sooner.
16	No.1 A/C Fin Ass	92	02/11/03	01/02/04	13,27, 35,44, 54,62, 67	This is the final assembly for the first aircraft and is envisaged to take 3 months.

Aerodynamic Testing

Task No.	Title	Length	Start Date	End Date	Predecessors	Comments
18	Basic Testing	365	02/09/98	01/09/99	5	The aircraft configuration must be defined in some detail before the aerodynamic testing may commence. This configuration is used for the initial control law design process.
19	Final Testing	730	02/09/99	31/08/01	18	After the final testing is complete, this model is used for the final control law development. However, due to the concurrent nature of this project, there would be further interactions to those displayed here.
20	Aerodynamic Model Available	1	01/09/01	01/09/01	19,10	The aerodynamics model is available for use. This may be complete, though not 100% representative of the final aircraft. The 20% release point is assumed to give the final aerodynamic model since the dimensions of the major components should be complete by this point in time.

Engine Development

Task No.	Title	Length	Start Date	End Date	Predecessors	Comments
22	Analyse Requirements	61	01/09/98	31/10/98	4	This is the time taken to analyse the engine requirements, including the required thrust, the accessory requirements etc. Two months will be required to do this task.
23	Tender	365	01/11/98	31/10/99	22	This is the time taken to tender for the engine design. It takes about a year to carry out this process, during which discussions should be made with a series of manufacturers.
24	Selection	1	01/11/99	01/11/99	23	Select the engine to be used for the aircraft
25	Development	1460	02/11/99	31/10/03	24	The total development period for the engine has been put at 4 years, after which flight ready engines should be available.
26	Model Available	730	02/11/99	31/10/01	24	The engine model should be available after two years, though modifications may be required to update the model at the point when the engines are finally available.
27	Engines Available	1	01/11/03	01/11/03	25	The final engines are available for the aircraft, and are ready to be installed on the wing.

Control Law Development

Task No.	Title	Length	Start Date	End Date	Predecessors	Comments
30	Initial Development	365	01/09/98	31/08/99	4	Perform the initial development work to filter some initial concepts.
31	Choose Concept	1	01/09/99	01/09/99	30	Choose the control law concept based on the results of the initial work.
32	Development #1	365	02/09/99	31/08/00	31,18	Perform the first set of development work to get some actual laws for hardware design.
33	Supply Initial Laws	1	01/09/00	01/09/00	32	Supply the initial laws based on the first series of hardware design work
34	Development #2	365	01/09/01	31/08/02	32,19	Perform the second series of control law evaluations to produce a first flight design
35	Supply Flight #1 Laws	1	01/09/02	01/09/02	34	Supply the first flight control laws
36	Flight Test Development	90	07/03/03	04/06/03	91	Develop the laws for the first flight
37	Supply Production Laws	1	05/06/03	05/06/03	36	Supply the production control laws

Flight Control System Hardware Development

Task No.	**Title**	**Length**	**Start Date**	**End Date**	**Predecessors**	**Comments**
39	Define Requirements	122	01/09/98	31/12/98	4	Six months required to develop the requirements for the FCS
40	Tender + Develop	365	01/01/99	31/12/99	39	One year to tender for the FCS .
41	Select Prime Contractor	1	01/01/00	01/01/00	40	Select the contractor at the end of the tender process.
42	Develop H/W	546	02/01/00	30/06/01	41	Eighteen months to develop the prototype hardware for the system.,
43	Initial FCS Boxes Available	1	01/07/01	01/07/01	42	Prototype hardware available.
44	Production H/W	364	02/07/01	30/06/02	43	One year to develop the production hardware from the prototype hardware.
45	Develop S/W	365	01/09/00	31/08/01	41,32	Develop the prototype software for the hardware boxes.
46	Production S/W	365	01/09/02	31/08/03	45,34	Develop the production software from the prototype hardware.
47	Flight Test	274	07/03/03	05/12/03	91,45,44	Flight test the flight control system.
48	Release to Service	1	01/09/03	01/09/03	46,44	Release to service.

Flight Management System Development

Task No.	Title	Length	Start Date	End Date	Predecessors	Comments
50	Define Requirements	184	01/09/98	03/03/99	4	This is the six months which it takes to analyse the requirements for the FMS and to produce a detailed specification.
51	Tender	366	04/03/99	03/03/00	50	This is the year which it takes to tender and decide which proposal to accept.
52	Select Prime Contractor	1	04/03/00	04/03/00	51	Select the prime contractor.
53	Prototype development	545	05/03/00	31/08/01	52	Eighteen months to get to the prototype stage once the proposal has been accepted.
54	Production Development	274	01/09/01	01/06/02	53	Nine months to take the prototype and develop it into the production hardware.
55	Flight Test Modifications	92	05/11/03	04/02/04	54,94	Three months to make the flight test modifications in light of the flight test campaign.
56	Release to Service	1	05/02/04	05/02/04	55	Release to service

Hydraulic System Development

Task No.	Title	Length	Start Date	End Date	Predecessors	Comments
59	Defined	184	01/09/98	03/03/99	4	Six months are required to define the hydraulic system. This takes place at the end of the initial configuration stage. Therefore the aircraft configuration is known, including the control surface locations and number, and also a basic schematic for the system would be available. At the end of this initial stage, these would be refined with more detail, and a good overview of the system available, including the requirements from the major users.
60	Developed	1096	04/03/99	03/03/02	59	Three years required to design the hydraulic system - the landing gear design is the limiting factor. This may be able to be reduced in the event of gear design being extracted from this particular task.
61	Tested	365	04/03/02	03/03/03	60	One year required to test the hydraulic system, and it must be before first flight.
62	Released	1	04/03/03	04/03/03	61	Release to test confirms system ready for flight. Additional testing beyond this is assumed for reliability purposes

Electrical System Development

Task No.	Title	Length	Start Date	End Date	Predecessors	Comments
64	Defined	184	01/09/98	03/03/99	4	Six months are required to define the electrical system. This takes place at the end of the initial configuration stage. Therefore the aircraft configuration is known, including the control surface locations and number, and also a basic schematic for the system would be available. At the end of this initial stage, these would be refined with more detail, and a good overview of the system available, including the requirements from the major users.
65	Developed	731	04/03/99	03/03/01	64	Two years to design and develop the system - need to liaise with the airframe during the routing process. Could probably be done much quicker
66	Tested	365	04/03/01	03/03/02	65	One year required to test the electrical system, and it must be before first flight
67	Released	1	04/03/02	04/03/02	66	Release to test confirms system ready for flight. Additional testing beyond this is assumed for reliability purposes

Engineering Simulation Development

This assumes that the engineering simulator is available. If the engineering simulator is not available then 18 months should be added to the front of this timescale for building and commissioning.

Task No.	Title	Length	Start Date	End Date	Predecessors	Comments
70	Code Model	91	01/11/01	30/01/02	19,26	Three months are required to code the model from the final model and engines becoming available. However, as the design progresses, previous models would enable the simulator to be programmed, and then this time at the end of release would be able to be decreased. In any case, the model would be continually improved as the aircraft enters service since modifications and errors would continually become apparent.
71	Final Model Test	181	31/01/02	30/07/02	70,72	Six months are required to validate the final model. This is a time where the hardware / software link may be confirmed, and the final model's performance verified.
72	Incorporate FCS HW Boxes	91	02/07/01	30/09/01	43	This assumes that previous models are available to enable the software / hardware links to be made.
73	Link to Iron Bird	92	01/10/01	31/12/01	72,86	This is where the simulator is formally linked to the iron bird. The iron bird should be constructed fully by the start of this phase.
74	Control Law Development	365	31/01/02	30/01/03	70	This is where the specific aircraft control law development starts, During previous studies the control laws would be developed using previous models. This is the phase allocated to control law development, including checking for normal flight, failure cases and any other required system interactions.
75	Test Pilot Training	61	02/09/02	01/11/02	71,72,35	This is two months of concentrated time which has been allocated for test pilot training, although the pilots would have been flying the aircraft during the development phase. During this phase, the first flight control laws should be available, along with production hardware, and the final model testing should be complete.

Training Simulator Development

The training simulator is used for pilot training. The following figures haven been assumed.

Task No.	Title	Length	Start Date	End Date	Predecessors	Comments
77	Code Aerodynamic Model	365	01/11/01	31/10/02	19,26	Coding the model takes one year or so from the completion of the majority of the aerodynamic testing. However, validation of the model may require time to be taken during the flight test program. In addition the engine model is required for the coding to commence.
78	Test Model	181	01/11/02	30/04/03	77	Testing the model takes six months or so. This is done to debug the software and to prepare the software for simulation. CHECK HOW THIS FITS IN WITH THE COMPLETE SIMULATOR TESTING.
79	Build Simulator	365	01/01/02	31/12/02	12	Rely on 80% release for the aircraft structure, since accurate cockpit hardware is required. Approximately one year has been allocated for this process.
80	Incorporate Systems	365	04/03/03	02/03/04	66,61,54 34,45,44	Require the majority of the control law development to be done(Development#2), the production FCS hardware to be available together with the development software, the production FMS, and finally the tested electrical and hydraulic systems. This results in the majority of the aircraft being defined, and therefore the simulator may be built with little risk of change.
81	Final Testing	62	03/03/04	03/05/04	79,78,80 93,94	Need systems to be tested, plus the aero data testing to be complete. This will then form the final qualification for the training simulator.
82	Certificate	1	04/05/04	04/05/04	81	This is when the simulator is certificated. for use, and airline training may commence.

Iron Bird Development

Task No.	Title	Length	Start Date	End Date	Predecessors	Comments
85	Define Requirements	92	04/03/99	03/06/99	39,50	The Iron Bird rig requirements depend on the FCS and FMS requirements. At this point, the interfaces are known for the FCS and FMS systems, and their expected reliability and failure modes.
86	Construct	366	04/06/99	03/06/00	85	It is expected to take 1 year to construct the iron bird rig.
87	Operate - proto	365	04/03/02	03/03/03	86,65,60 53,43,45	Prototype hardware is required for the appropriate systems, as is the hardware for the electrical and hydraulic systems.
88	Operate - prod	365	01/09/03	30/08/04	87,54,46 44	Production hardware is required to operate the rig in this mode.

Flight Test

Task No.	**Title**	**Length**	**Start Date**	**End Date**	**Predecessors**	**Comments**
90	Release to test	1	05/03/03	05/03/03	87,62	Confirm that the aircraft may be flight tested.
91	First Flight	1	06/03/03	06/03/03	90	The first flight of the aircraft
93	Aero Data Test	182	07/03/03	04/09/03	91	Six months to do the aerodynamic data testing
94	Systems Testing	243	07/03/03	04/11/03	91	Eight months to do the systems testing
95	Reliability Testing	274	07/03/03	05/12/03	91	Nine months to do the reliability testing
96	Certification Consolidation	30	04/05/04	02/06/04	93,94,95 101	One month required to consolidate the information gained during the testing process for the final certification documentation.

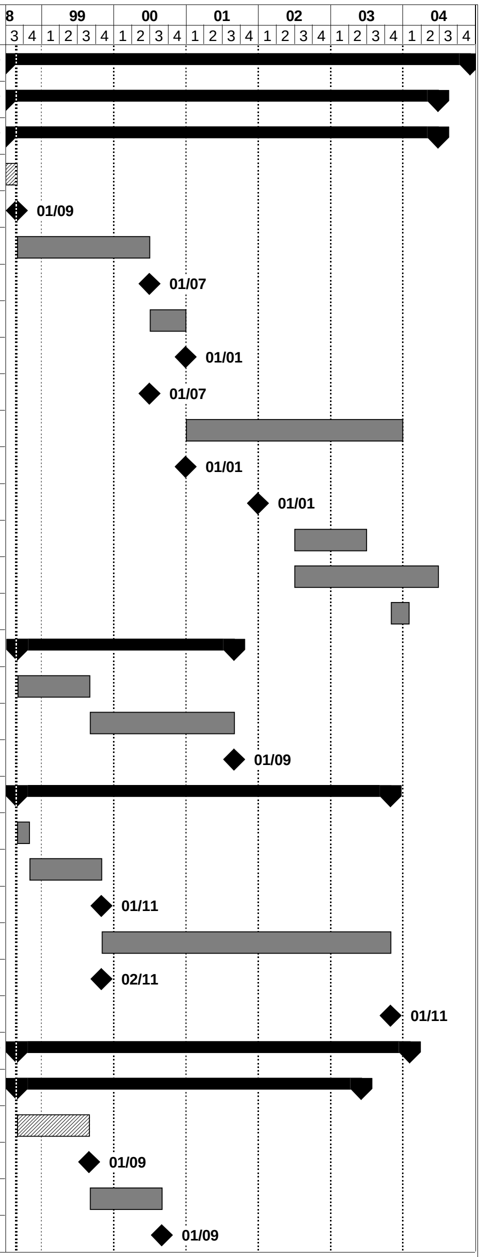
Miscellaneous Documentation

Task No.	Title	Length	Start Date	End Date	Predecessors	Comments
99	Technical Manuals	731	01/01/02	01/01/04	12	Assume that it takes two years to generate the technical manuals. This process can start when 80% of the design has been released.
100	Flight Manuals	366	01/09/02	01/09/03	65,60,54 44,34,26 19,13	Generate the flight manuals. For this, the aircraft systems, the flight hardware, the engine and the airframe models need to be complete, though modifications may be required in light of the flight test program.
101	Certification Documentation	123	02/01/04	03/05/04	99,100	The certification documentation which requires either of the flight test manuals is assumed to take 4 months from the completion of this documentation.

Certification Documentation

Task No.	Title	Length	Start Date	End Date	Predecessors	Comments
103	Plan	184	02/09/99	03/03/00	4,31	This is the first six months which are required to plan the certification process.
104	Present	1	04/03/00	04/03/00	103	Present the proposed certification basis to the certification authority.
105	Perform	1736	05/03/00	04/12/04	104	This is the four and a half years that is the minimum time it takes to certify the aircraft.
106	Certificate	1	05/12/04	05/12/04	105,101, 96,88	This is the final certification day, and for the aircraft to be certified, the documentation must be complete, the certification process must have been performed, and the results from the flight test program consolidated.
107	Service Entry	1	06/12/04	06/12/04	106	Projected service entry date

ID	Task Name	Duration	Start	Finish
1	**GRA Aircraft Project**	**2351d**	**01/07/98**	**06/12/04**
2	**Airframe**	**2191d**	**01/07/98**	**29/06/04**
3	**Airframe Developmer**	**2191d**	**01/07/98**	**29/06/04**
4	Initial Configuratio	62d	01/07/98	31/08/98
5	Define Configurati	1d	01/09/98	01/09/98
6	Develop Configura	669d	01/09/98	30/06/00
7	Configuration Fixe	1d	01/07/00	01/07/00
8	Verify with Airlines	183d	02/07/00	31/12/00
9	Configuration Froz	1d	01/01/01	01/01/01
10	20% release	184d	01/07/00	31/12/00
11	Long lead items e	1095d	01/01/01	31/12/03
12	80% release	365d	01/01/01	31/12/01
13	100% release	181d	01/01/02	30/06/02
14	Static Tests	366d	01/07/02	01/07/03
15	Major manufacture	730d	01/07/02	29/06/04
16	No.1 A/C Fin Ass	92d	02/11/03	01/02/04
17	**Aerodynamic**	**1096d**	**02/09/98**	**01/09/01**
18	Basic Testing	365d	02/09/98	01/09/99
19	Final Testing	730d	02/09/99	31/08/01
20	Aerodynamic Mod	1d	01/09/01	01/09/01
21	**Engines**	**1888d**	**01/09/98**	**01/11/03**
22	Analyse Requirem	61d	01/09/98	31/10/98
23	Tender	365d	01/11/98	31/10/99
24	Selection	1d	01/11/99	01/11/99
25	Development	1460d	02/11/99	31/10/03
26	Model Available	730d	02/11/99	31/10/01
27	Engines Available	1d	01/11/03	01/11/03
28	**Flight Avionics**	**1984d**	**01/09/98**	**05/02/04**
29	**Control Laws**	**1739d**	**01/09/98**	**05/06/03**
30	Initial Developmen	365d	01/09/98	31/08/99
31	Choose Concept	1d	01/09/99	01/09/99
32	Development #1	365d	02/09/99	31/08/00
33	Supply Initial Laws	1d	01/09/00	01/09/00

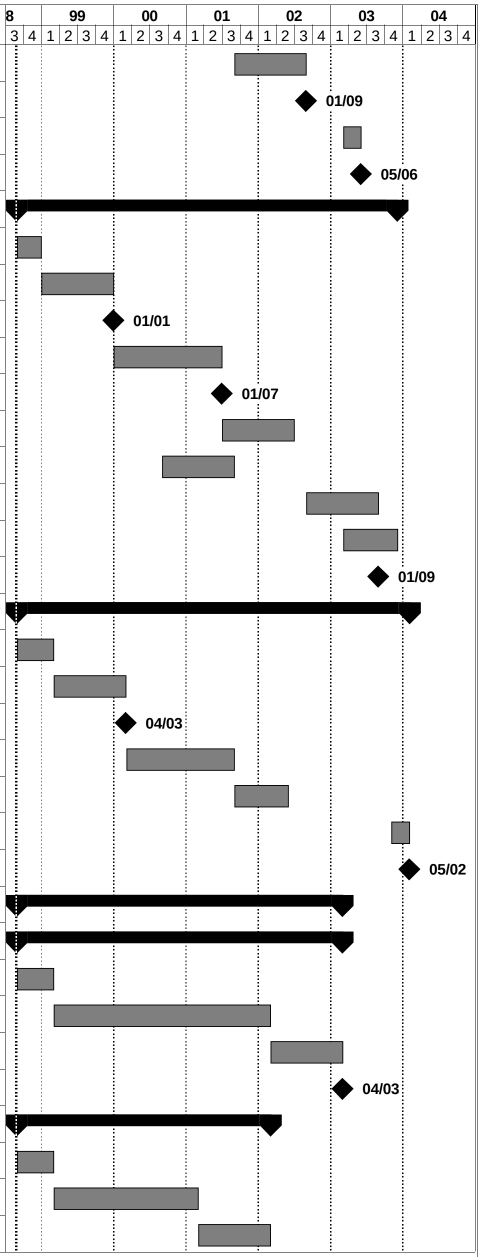


Project:
Date: 24/08/98

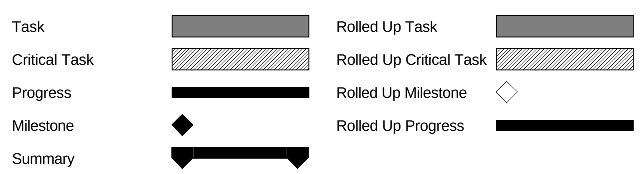
Task
Critical Task
Progress
Milestone
Summary
Rolled Up Task
Rolled Up Critical Task
Rolled Up Milestone
Rolled Up Progress

Page 1

ID	Task Name	Duration	Start	Finish
34	Development #2	365d	01/09/01	31/08/02
35	Supply Flight #1 L	1d	01/09/02	01/09/02
36	Flight Test Develo	90d	07/03/03	04/06/03
37	Supply Production	1d	05/06/03	05/06/03
38	**FCS**	**1922d**	**01/09/98**	**05/12/03**
39	Define Requireme	122d	01/09/98	31/12/98
40	Tender + Develop	365d	01/01/99	31/12/99
41	Select Prime Cont	1d	01/01/00	01/01/00
42	Develop H/W	546d	02/01/00	30/06/01
43	Initial FCS Boxes ,	1d	01/07/01	01/07/01
44	Production H/W	364d	02/07/01	30/06/02
45	Develop S/W	365d	01/09/00	31/08/01
46	Production S/W	365d	01/09/02	31/08/03
47	Flight Test	274d	07/03/03	05/12/03
48	Release to Service	1d	01/09/03	01/09/03
49	**FMS**	**1984d**	**01/09/98**	**05/02/04**
50	Define Requireme	184d	01/09/98	03/03/99
51	Tender	366d	04/03/99	03/03/00
52	Select Prime Cont	1d	04/03/00	04/03/00
53	Prototype Develop	545d	05/03/00	31/08/01
54	Production Develo	274d	01/09/01	01/06/02
55	Flight Test Modific	92d	05/11/03	04/02/04
56	Release to Service	1d	05/02/04	05/02/04
57	**Systems**	**1646d**	**01/09/98**	**04/03/03**
58	**Hydraulics**	**1646d**	**01/09/98**	**04/03/03**
59	Defined	184d	01/09/98	03/03/99
60	Developed	1096d	04/03/99	03/03/02
61	Tested	365d	04/03/02	03/03/03
62	Released	1d	04/03/03	04/03/03
63	**Electrics**	**1281d**	**01/09/98**	**04/03/02**
64	Defined	184d	01/09/98	03/03/99
65	Developed	731d	04/03/99	03/03/01
66	Tested	365d	04/03/01	03/03/02



Project:
Date: 24/08/98



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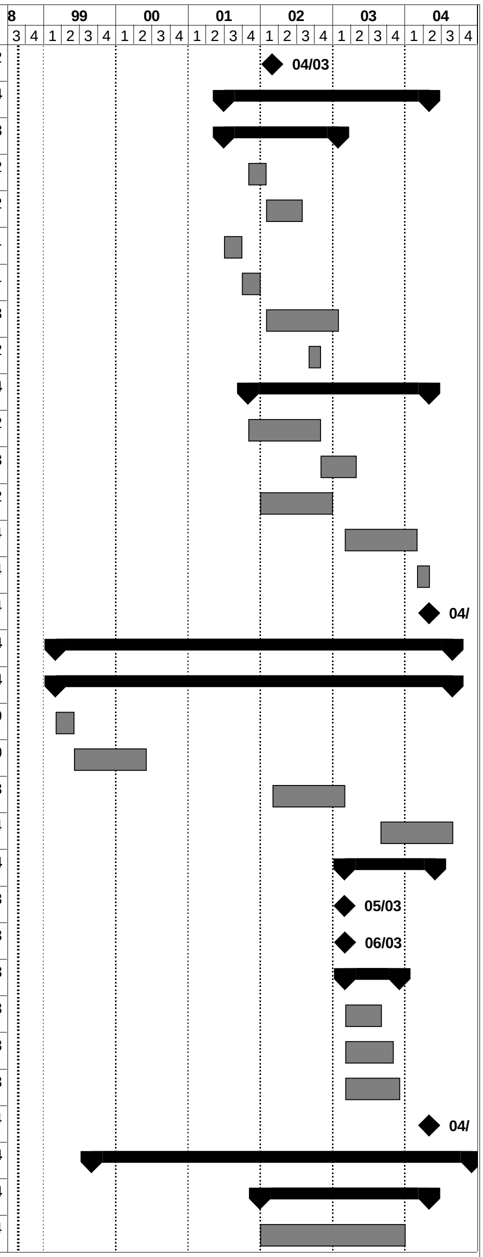
ID	Task Name	Duration	Start	Finish
67	Released	1d	04/03/02	04/03/02
68	**Simulation**	**1038d**	**02/07/01**	**04/05/04**
69	**Engineering Simulatc**	**578d**	**02/07/01**	**30/01/03**
70	Code Model	91d	01/11/01	30/01/02
71	Final Model Test	181d	31/01/02	30/07/02
72	Incorporate FCS I	91d	02/07/01	30/09/01
73	Link to Iron Bird	92d	01/10/01	31/12/01
74	Control Law Devel	365d	31/01/02	30/01/03
75	Test Pilot Training	61d	02/09/02	01/11/02
76	**Training Simulator**	**916d**	**01/11/01**	**04/05/04**
77	Code Aerodynami	365d	01/11/01	31/10/02
78	Test Model	181d	01/11/02	30/04/03
79	Build Simulator Ha	365d	01/01/02	31/12/02
80	Incorporate Syster	365d	04/03/03	02/03/04
81	Final Testing	62d	03/03/04	03/05/04
82	Certificate	1d	04/05/04	04/05/04
83	**Test Facilities**	**2007d**	**04/03/99**	**30/08/04**
84	**Iron Bird**	**2007d**	**04/03/99**	**30/08/04**
85	Define Requireme	92d	04/03/99	03/06/99
86	Construct	366d	04/06/99	03/06/00
87	Operate - proto	365d	04/03/02	03/03/03
88	Operate - prod	365d	01/09/03	30/08/04
89	**Flight Test**	**456d**	**05/03/03**	**02/06/04**
90	Release to test	1d	05/03/03	05/03/03
91	First Flight	1d	06/03/03	06/03/03
92	**Flight Testing**	**274d**	**07/03/03**	**05/12/03**
93	Aero Data Te	182d	07/03/03	04/09/03
94	Systems Tes	243d	07/03/03	04/11/03
95	Reliability Te	274d	07/03/03	05/12/03
96	Certification Cons	30d	04/05/04	02/06/04
97	**Docs + Cert**	**1922d**	**02/09/99**	**05/12/04**
98	**Documentation**	**854d**	**01/01/02**	**03/05/04**
99	Technical Manual	731d	01/01/02	01/01/04



Project:
Date: 24/08/98

Task		Rolled Up Task	
Critical Task		Rolled Up Critical Task	
Progress		Rolled Up Milestone	
Milestone		Rolled Up Progress	
Summary			

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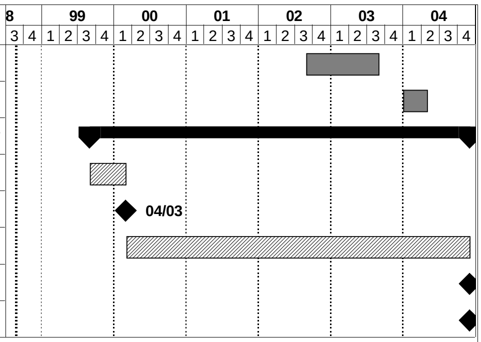
ID	Task Name	Duration	Start	Finish
100	Flight Manuals	366d	01/09/02	01/09/03
101	Certification Docu	123d	02/01/04	03/05/04
102	**Certification**	**1922d**	**02/09/99**	**05/12/04**
103	Plan	184d	02/09/99	03/03/00
104	Present	1d	04/03/00	04/03/00
105	Perform	1736d	05/03/00	04/12/04
106	Certificate	1d	05/12/04	05/12/04
107	Service Entry	1d	06/12/04	06/12/04



Project:
Date: 24/08/98

Task	Rolled Up Task
Critical Task	Rolled Up Critical Task
Progress	Rolled Up Milestone
Milestone	Rolled Up Progress
Summary	

B Results of the Extended Investigation of Flying Qualities Criteria against Past Research Programmes

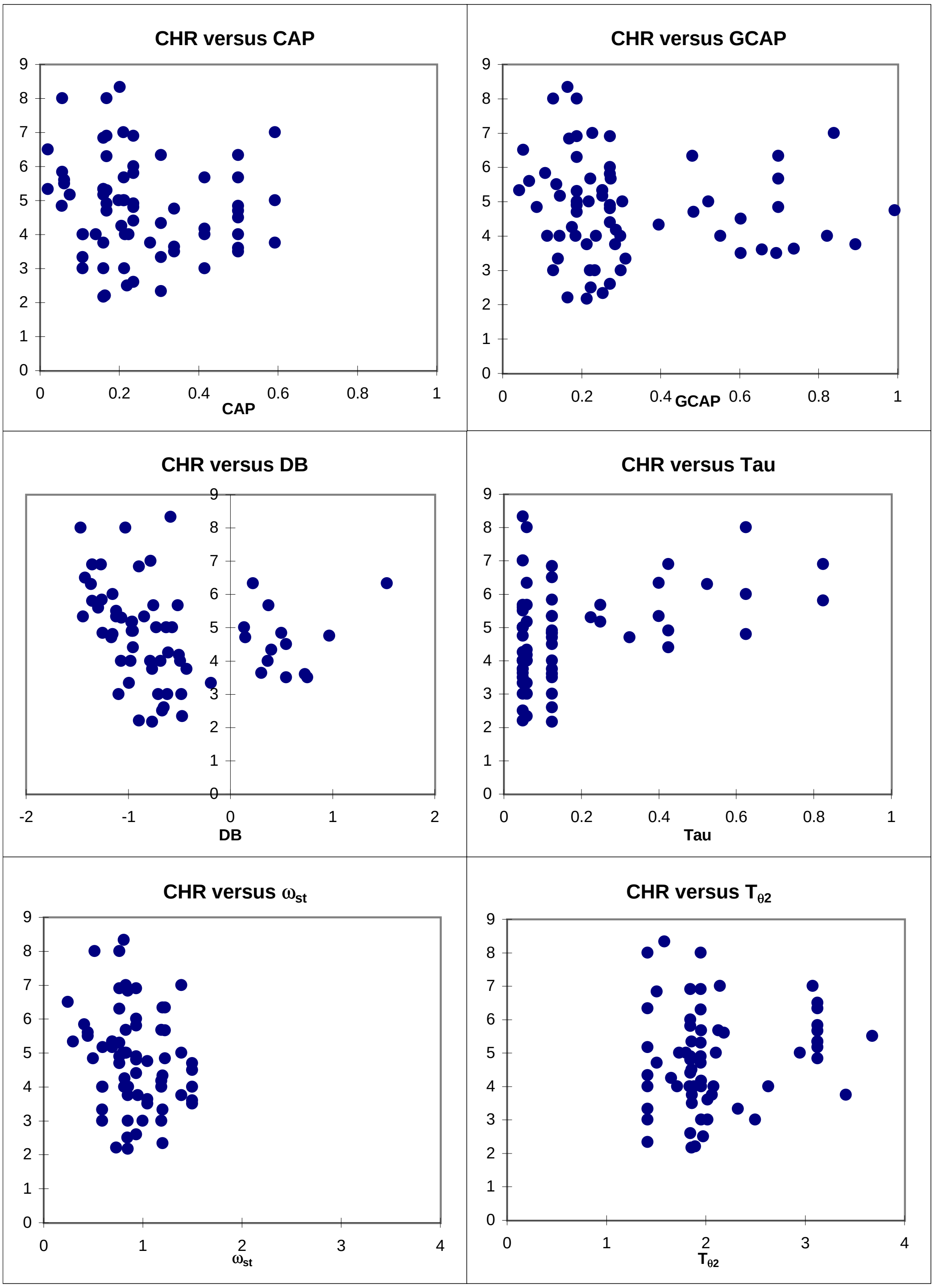


Figure B.1: All Motion Sim Laws Plot Set 1

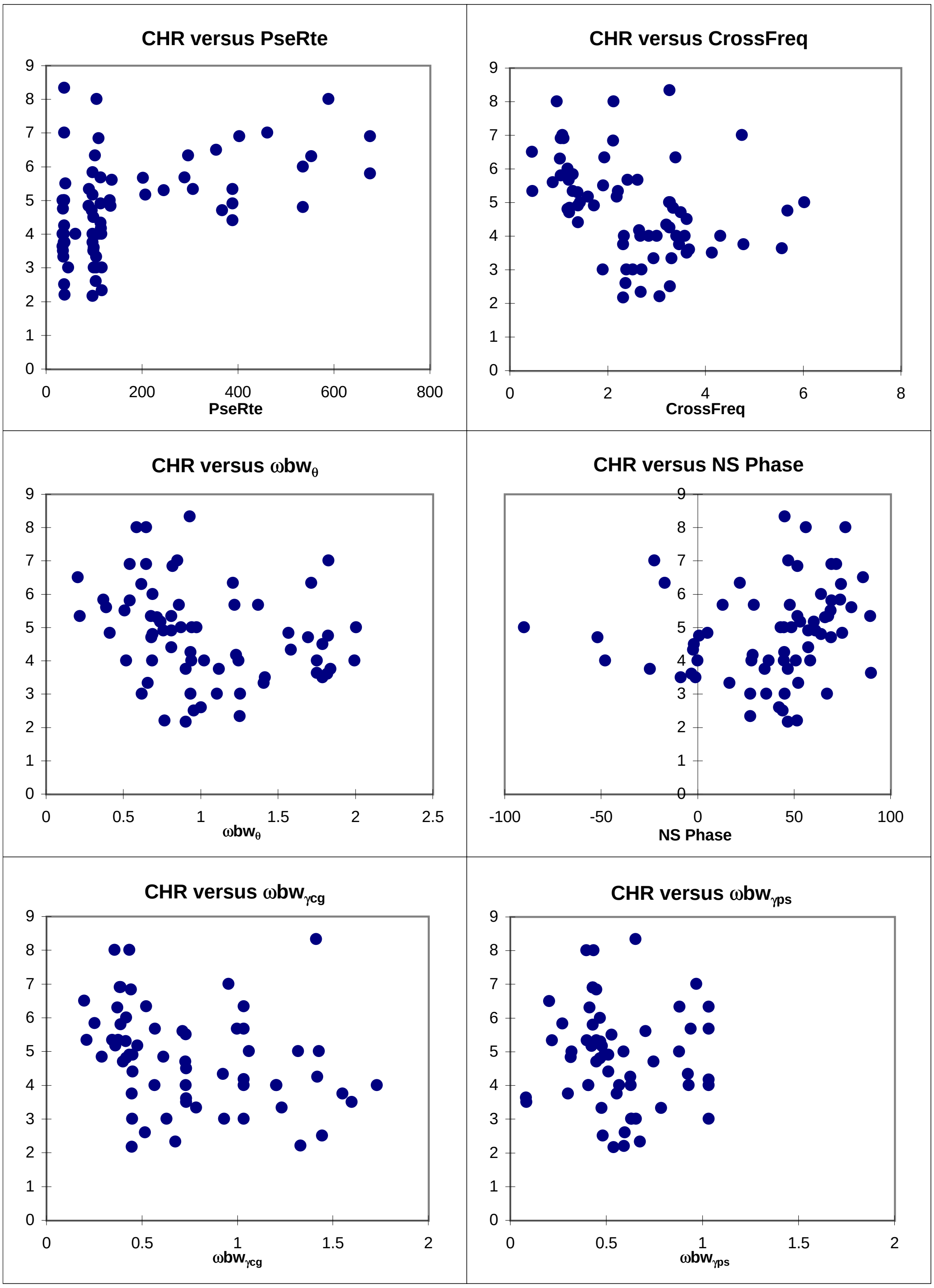


Figure B.2: All Motion Sim Laws Plot Set 2

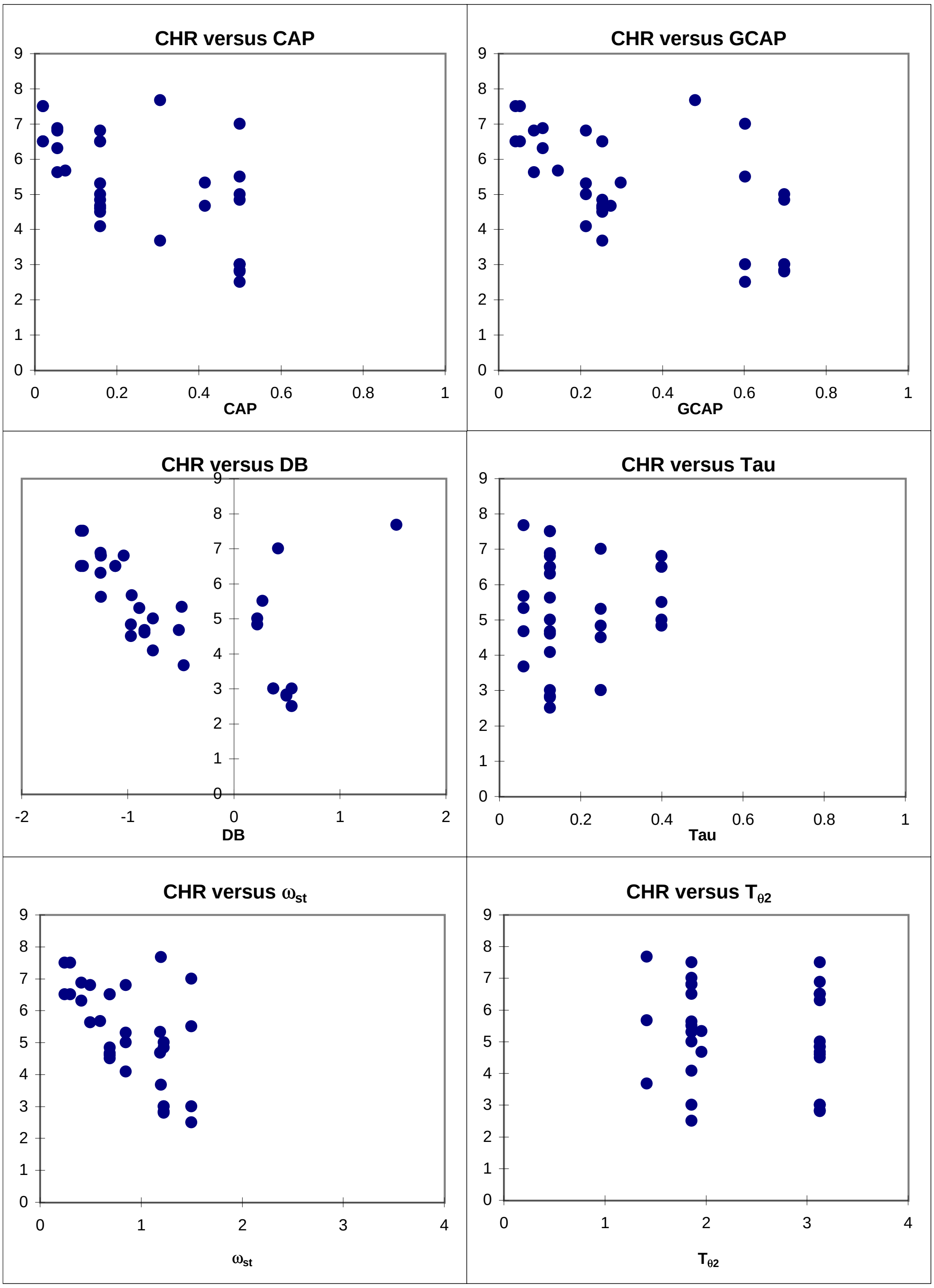


Figure B.3: All TIFS Laws Plot Set 1

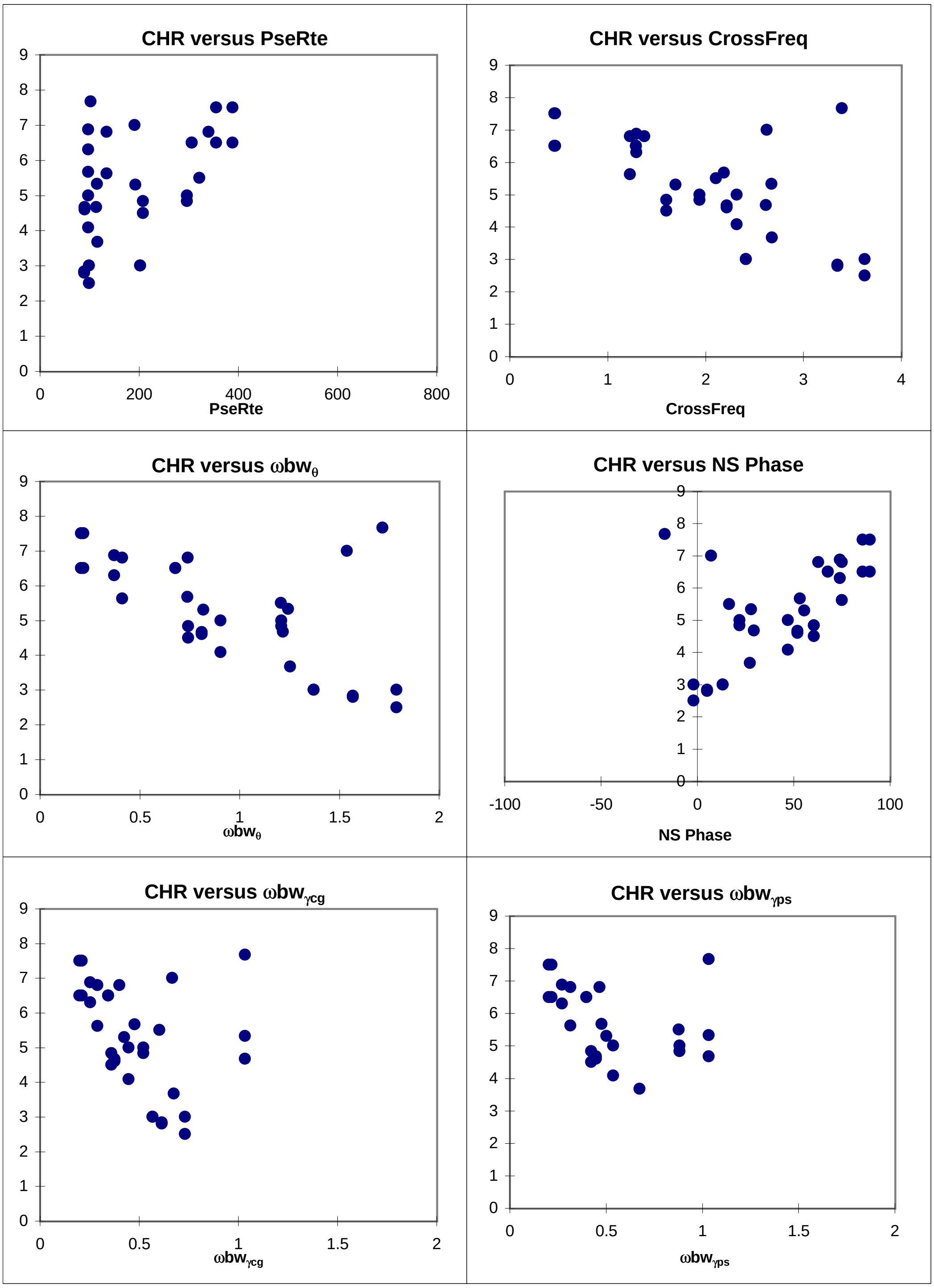


Figure B.4: All TIFS Laws Plot Set 2

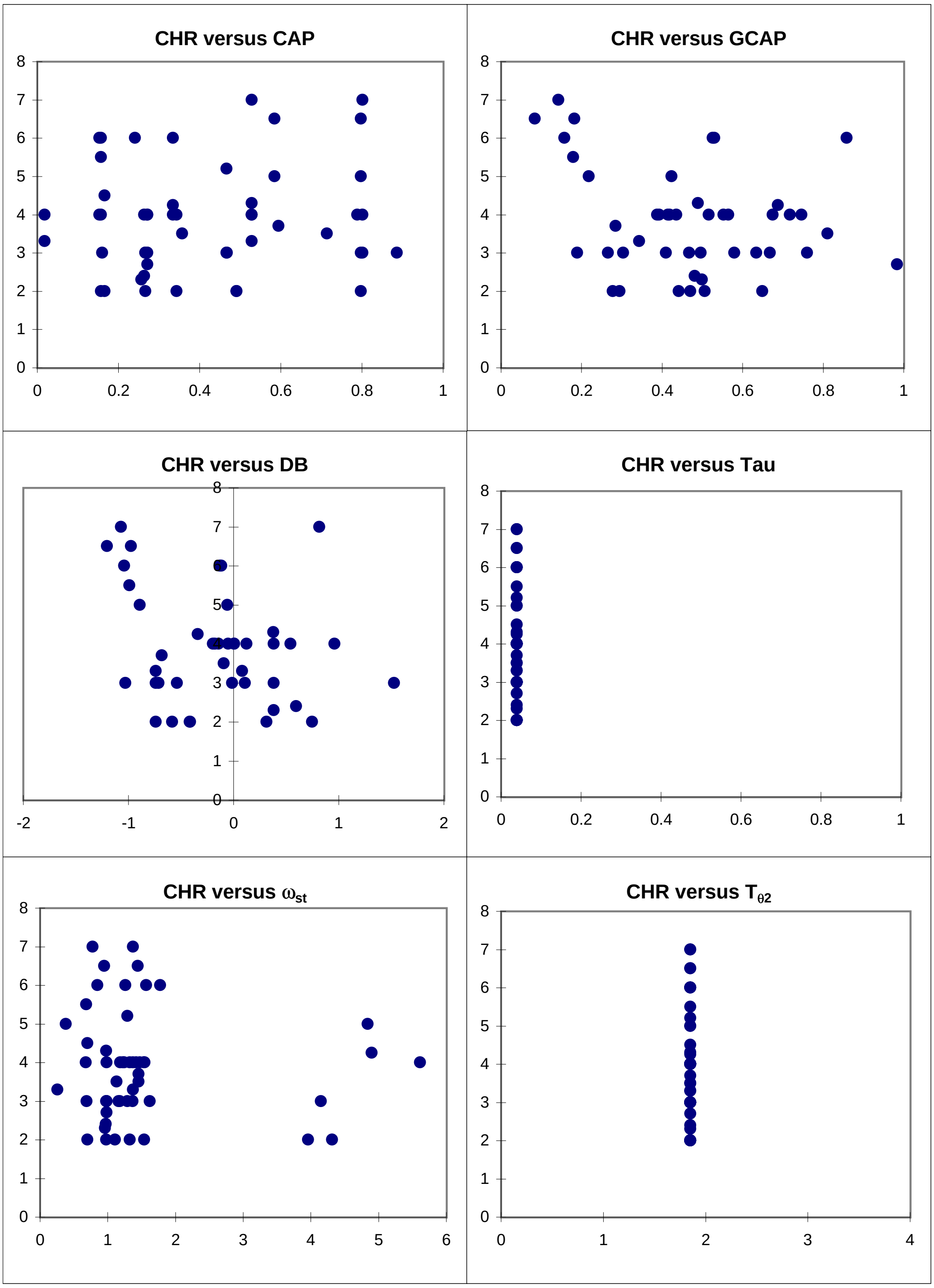


Figure B.5: All Fixed Base Laws Plot Set 1

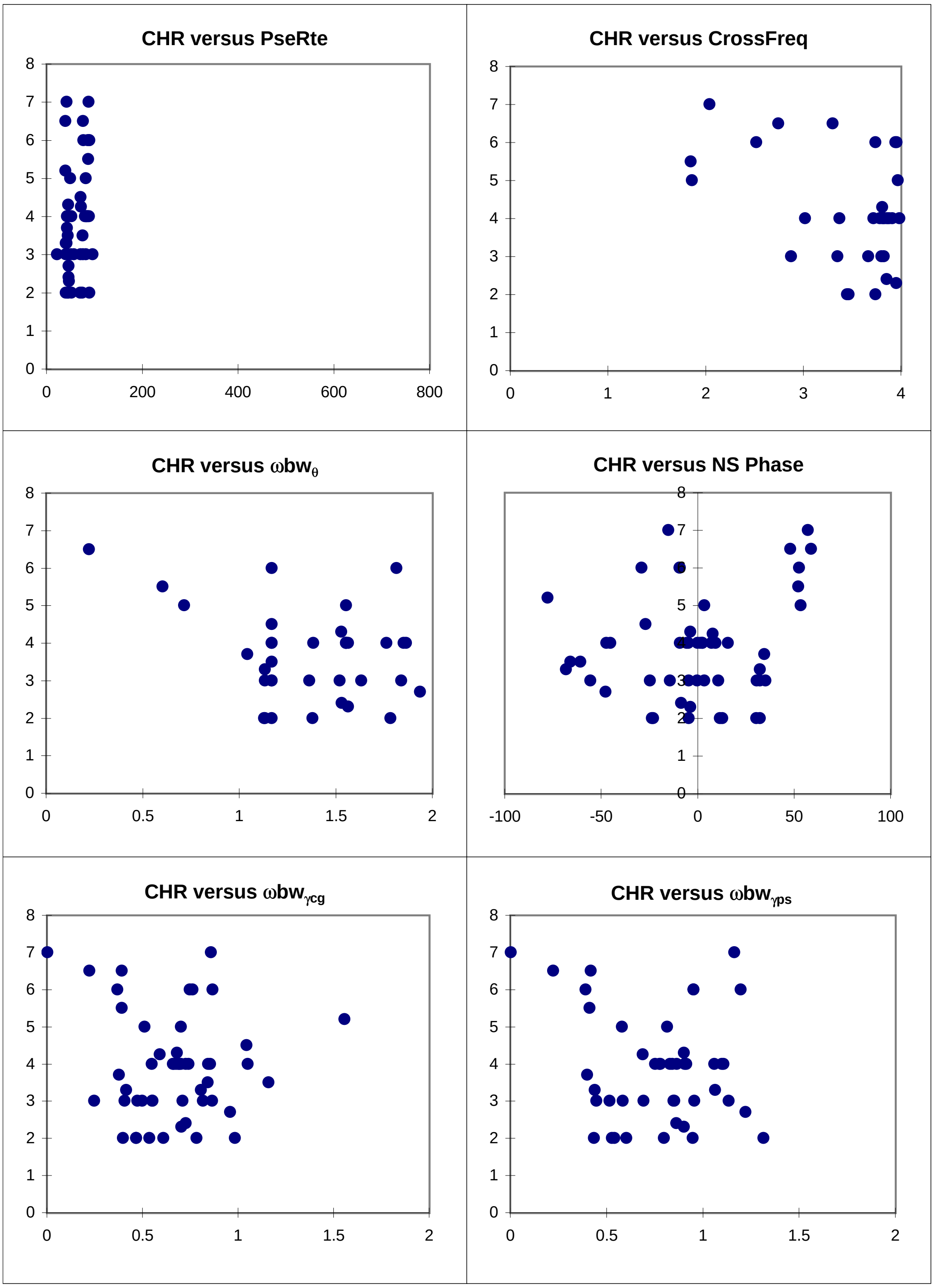


Figure B.6: All Fixed Base Laws Plot Set 2

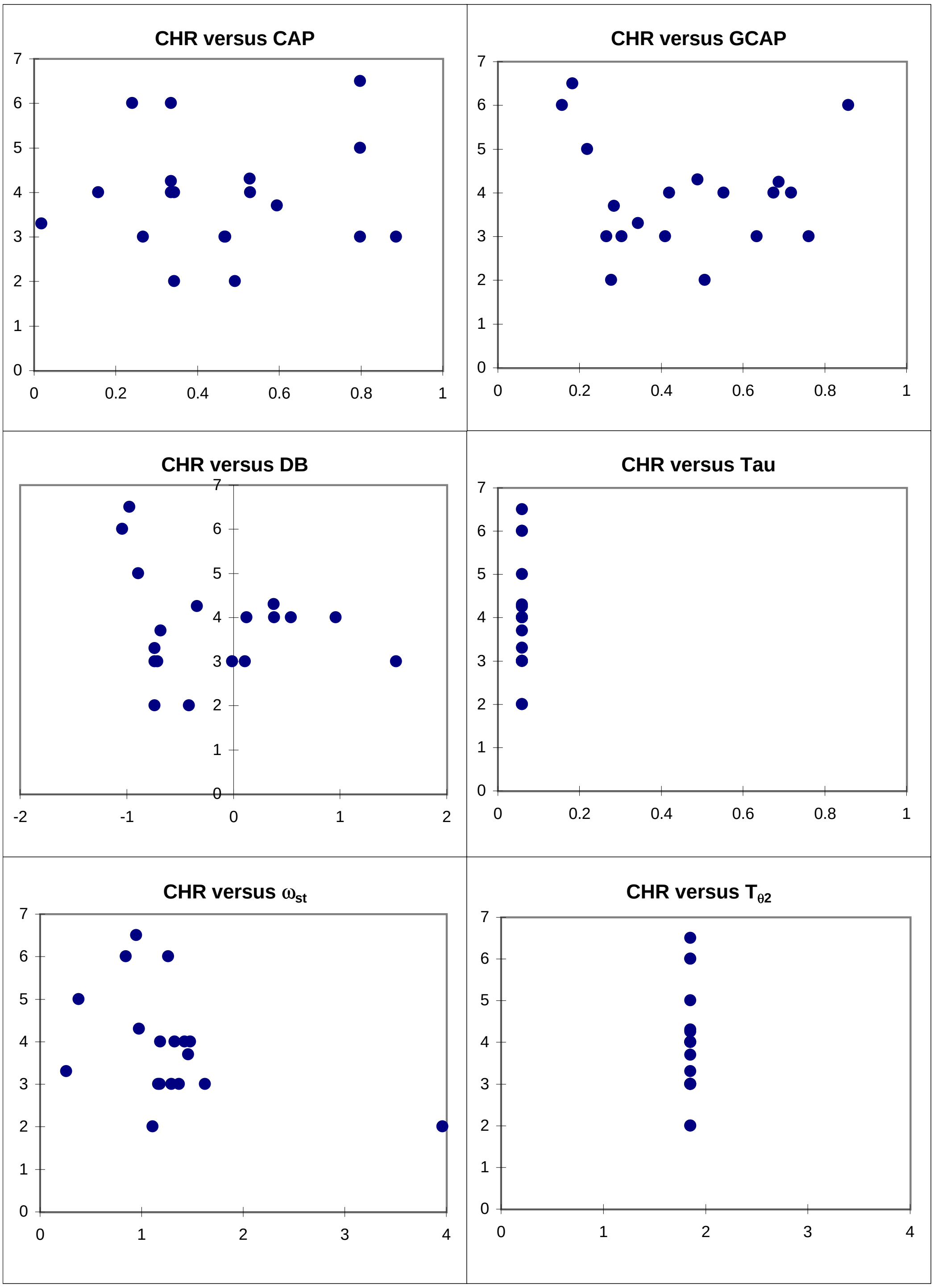


Figure B.7: All Fixed Base Pitch Rate Laws Plot Set 1

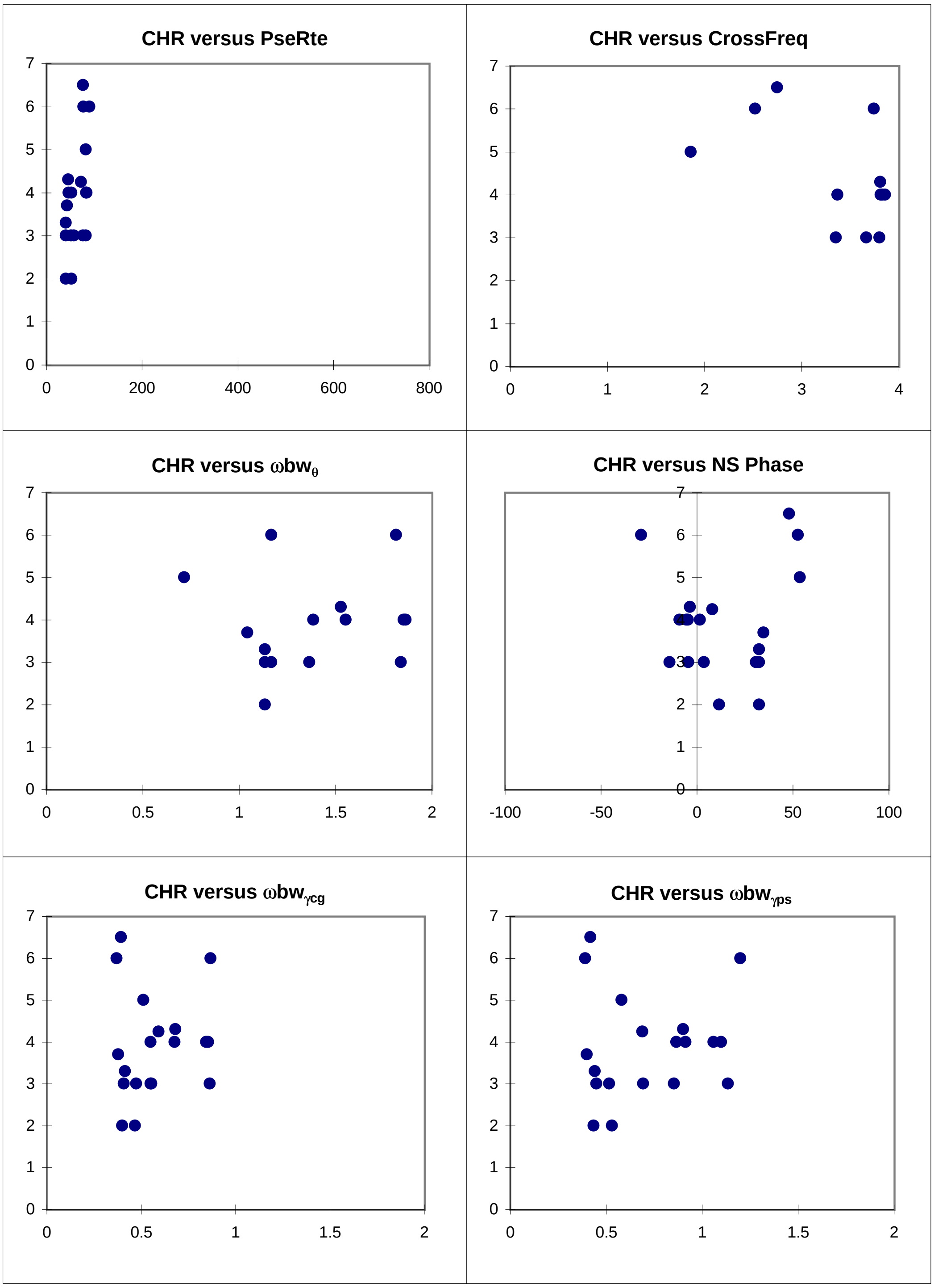


Figure B.8: All Fixed Base Pitch Rate Laws Plot Set 2

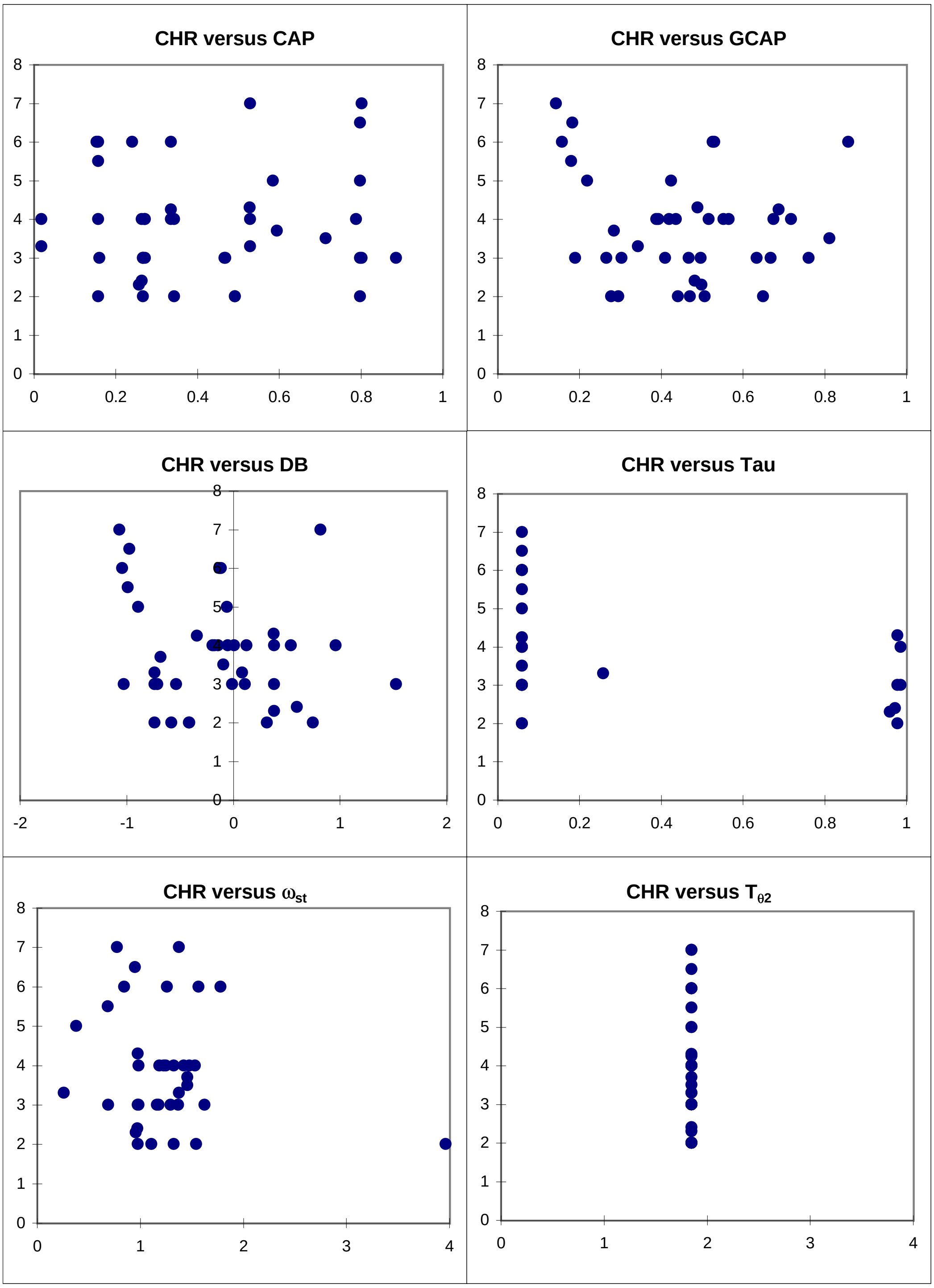


Figure B.9: All Fixed Base Rate Laws Plot Set 1

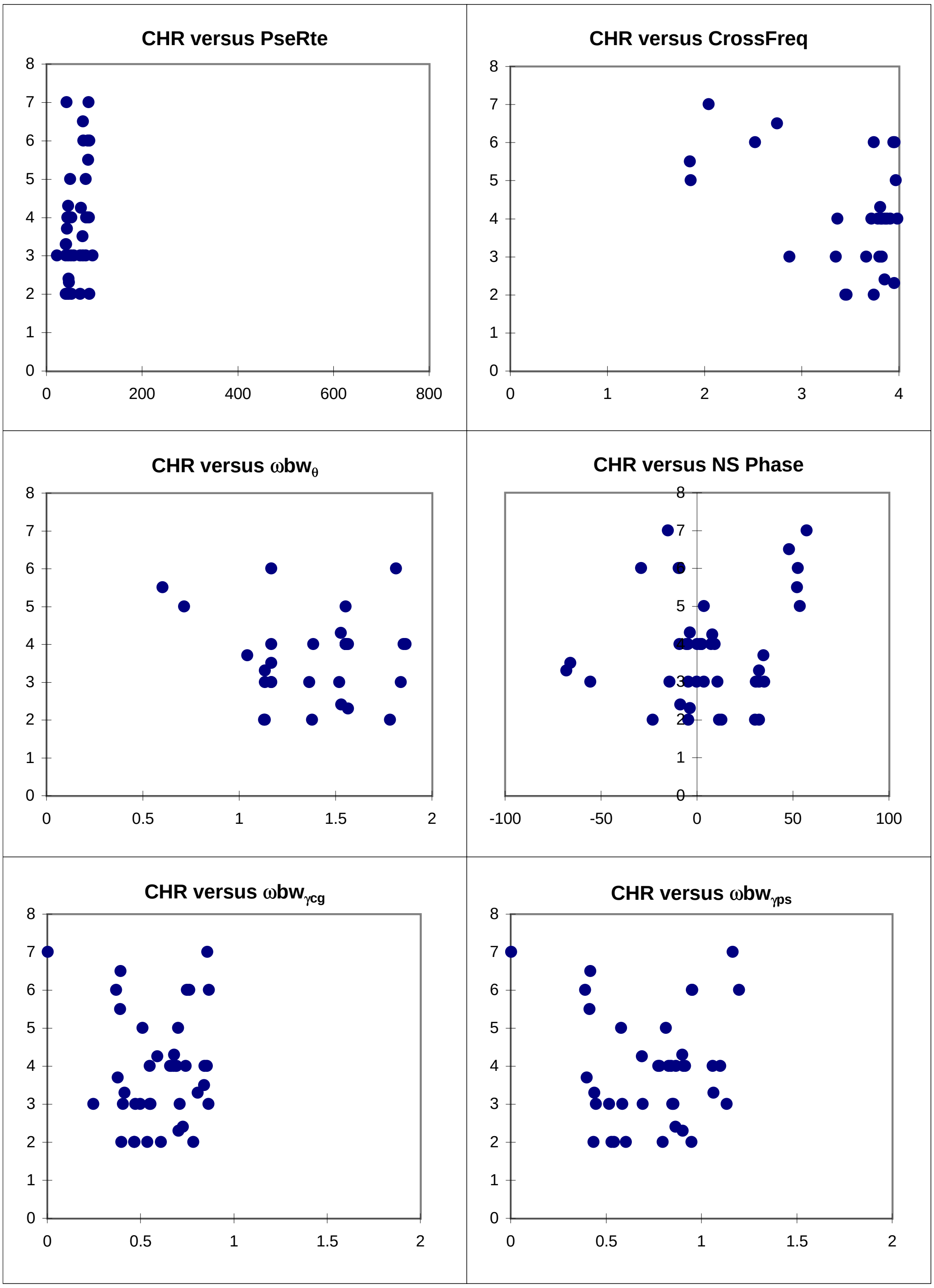


Figure B.10: All Fixed Base Rate Laws Plot Set 2

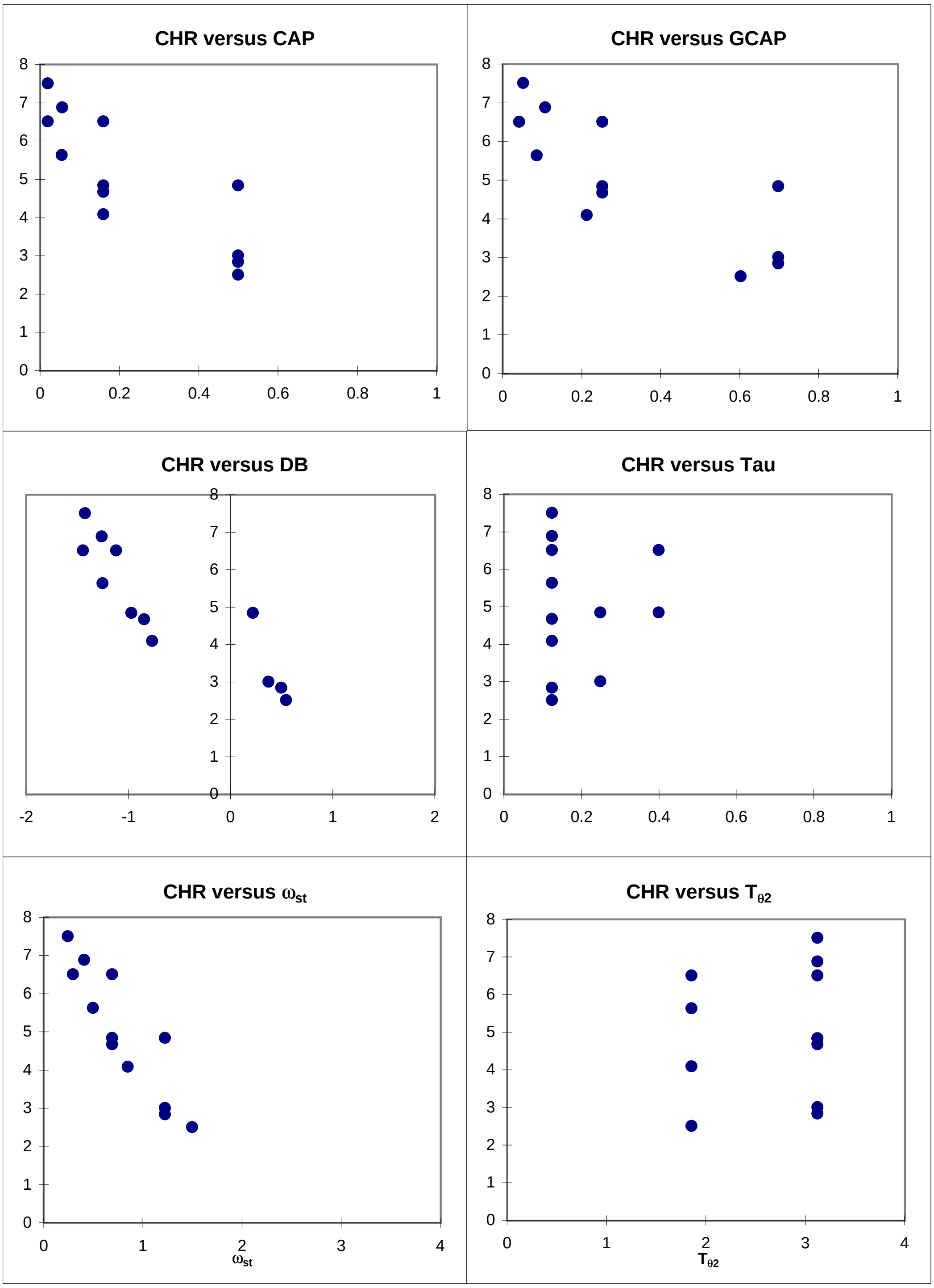


Figure B.11: AIAA 94-3489 TIFS Plot Set 1

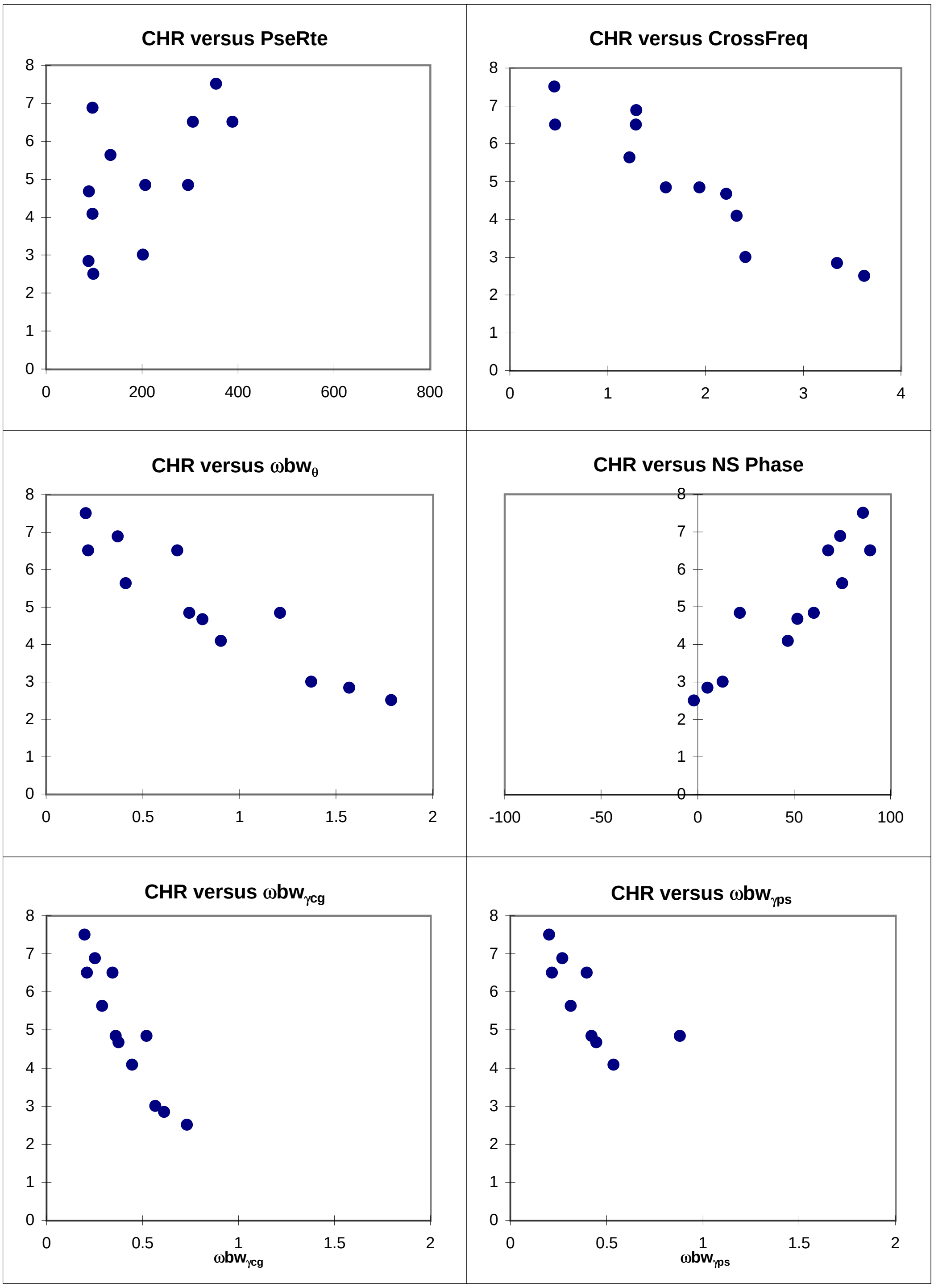


Figure B.12: AIAA 94-3489 TIFS Plot Set 2

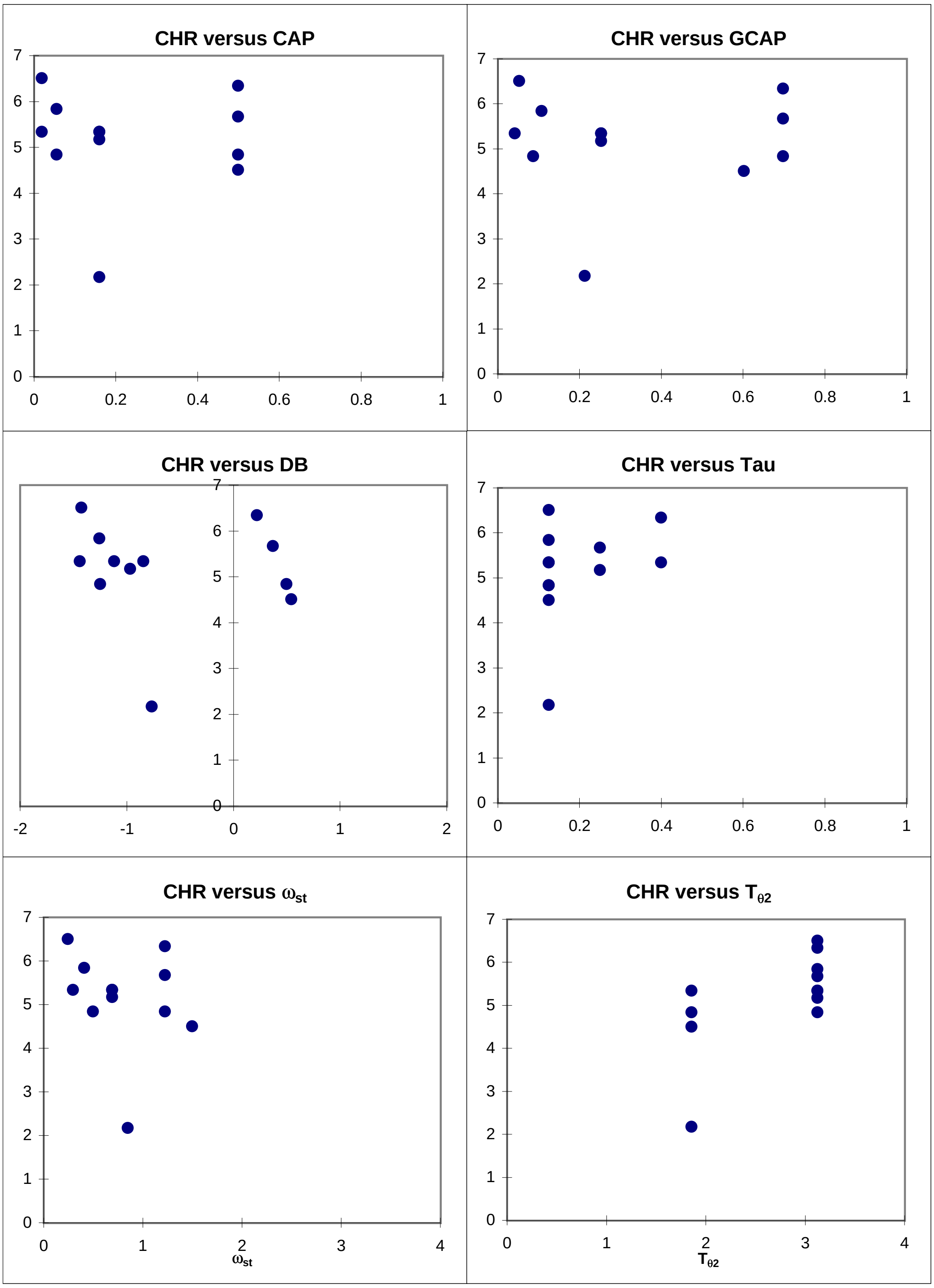


Figure B.13: AIAA 94-3489 VMS Plot Set 1

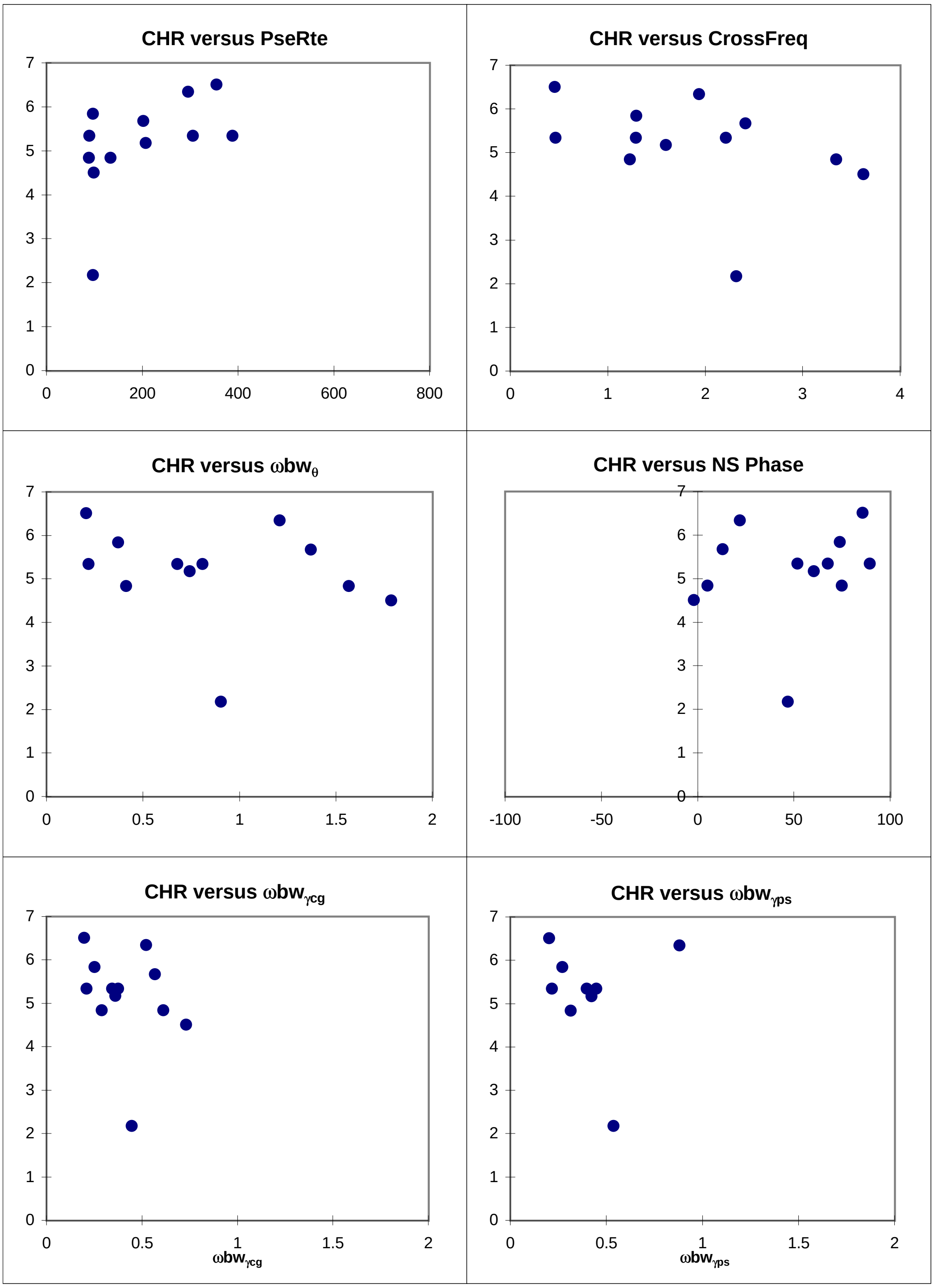


Figure B.14: AIAA 94-3489 VMS Plot Set 2

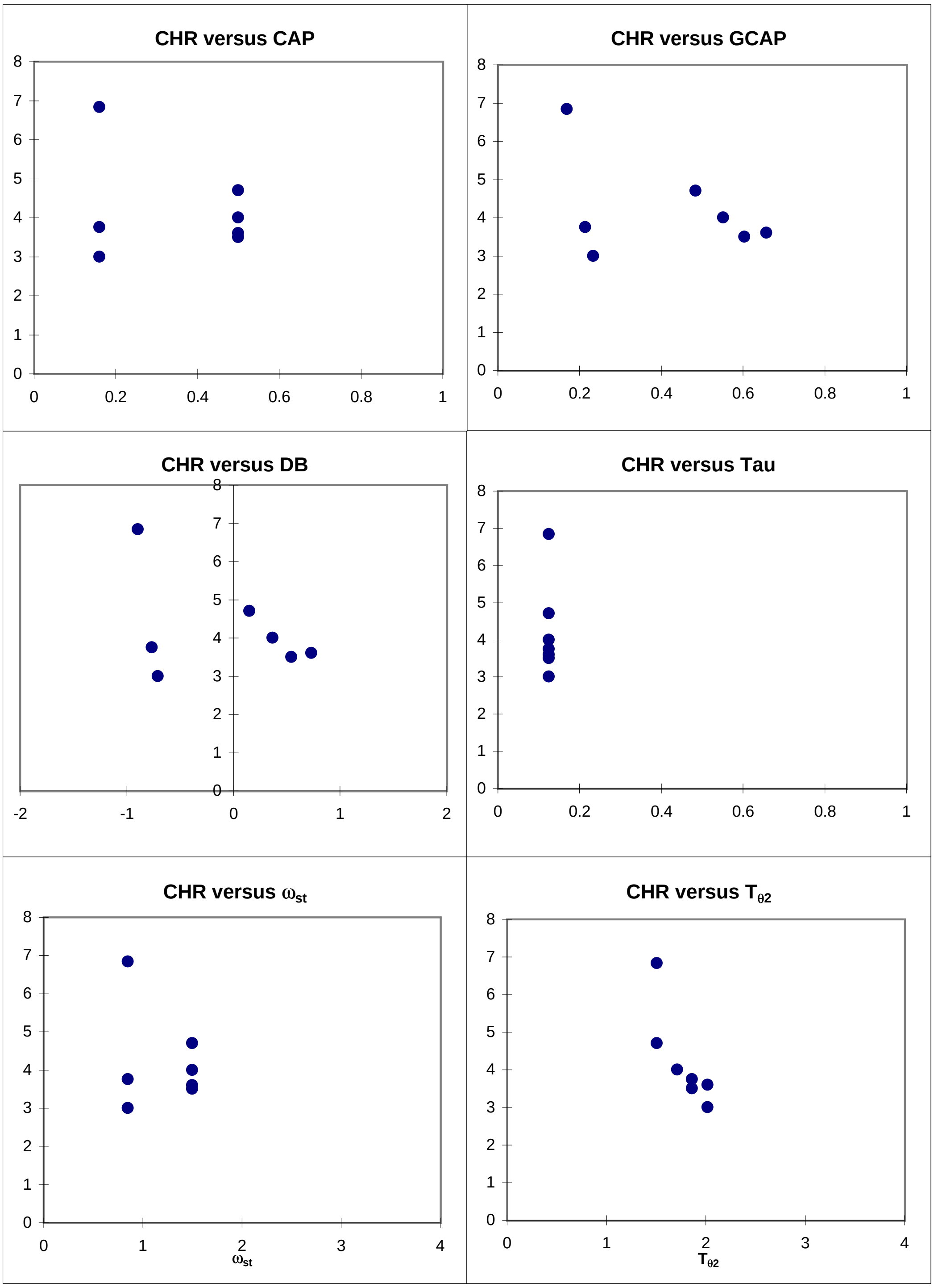


Figure B.15: AIAA 94-3510 Plot Set 1

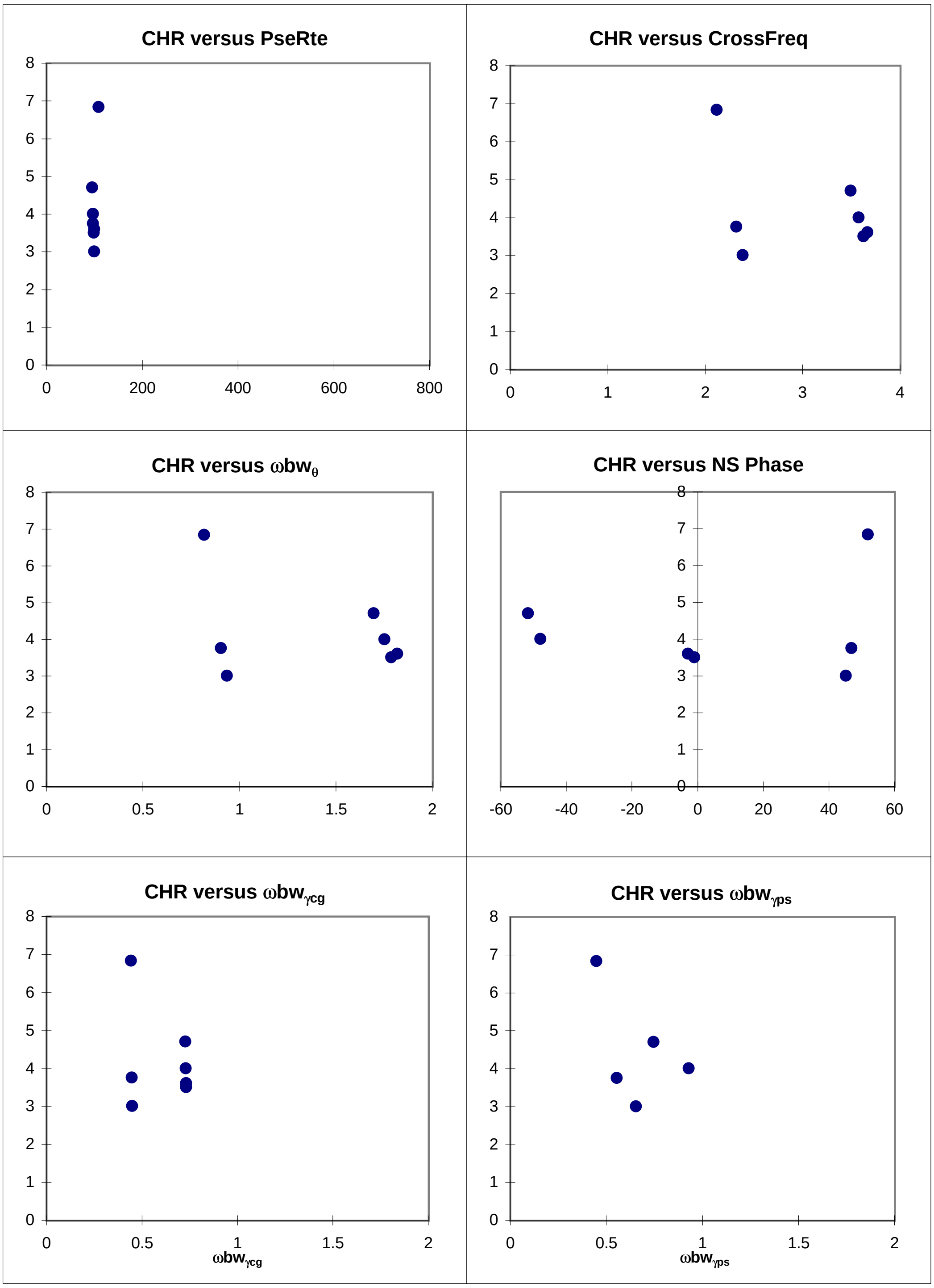


Figure B.16: AIAA 94-3510 Plot Set 2

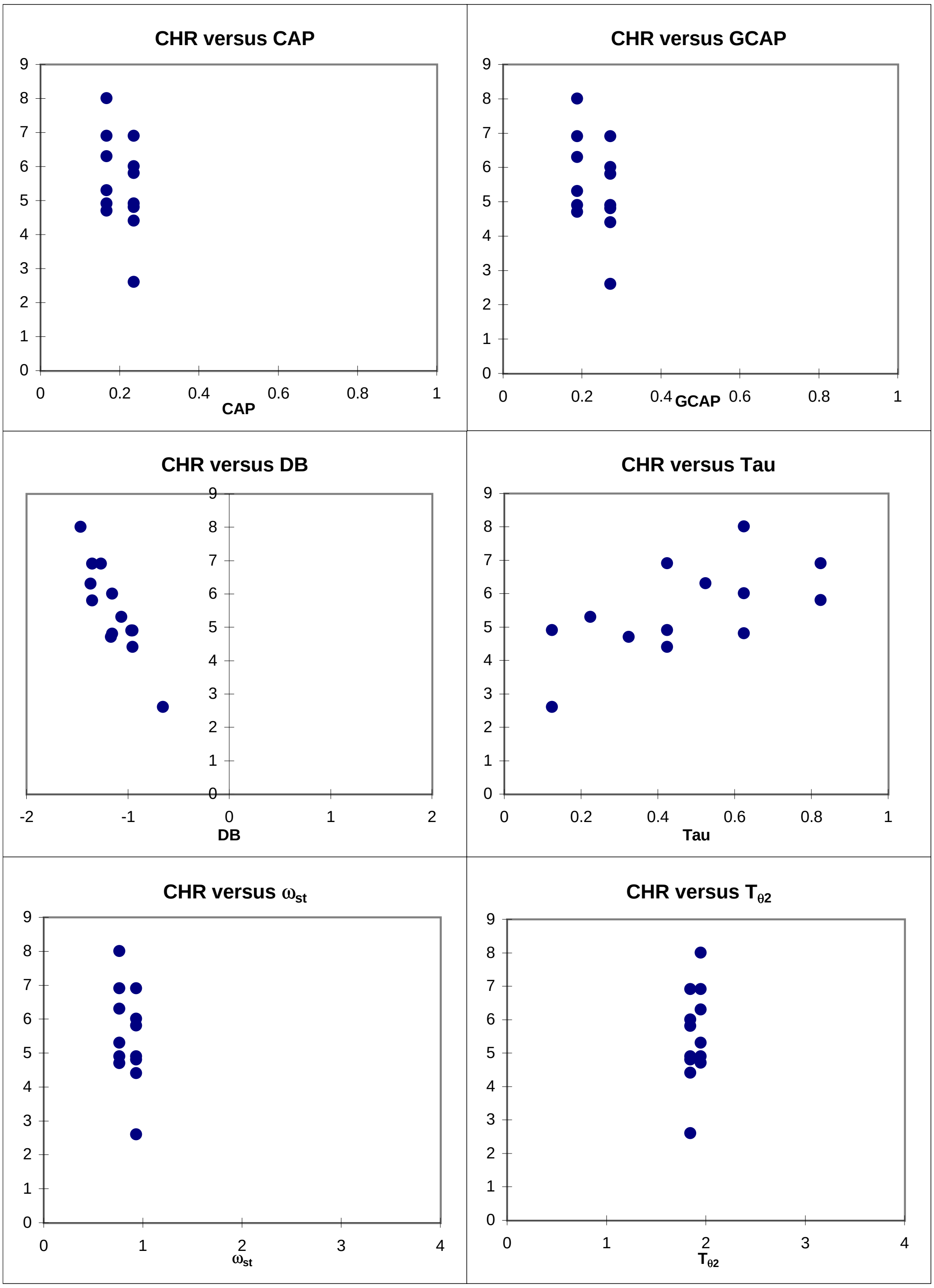


Figure B.17: AIAA 93-3815 Plot Set 1

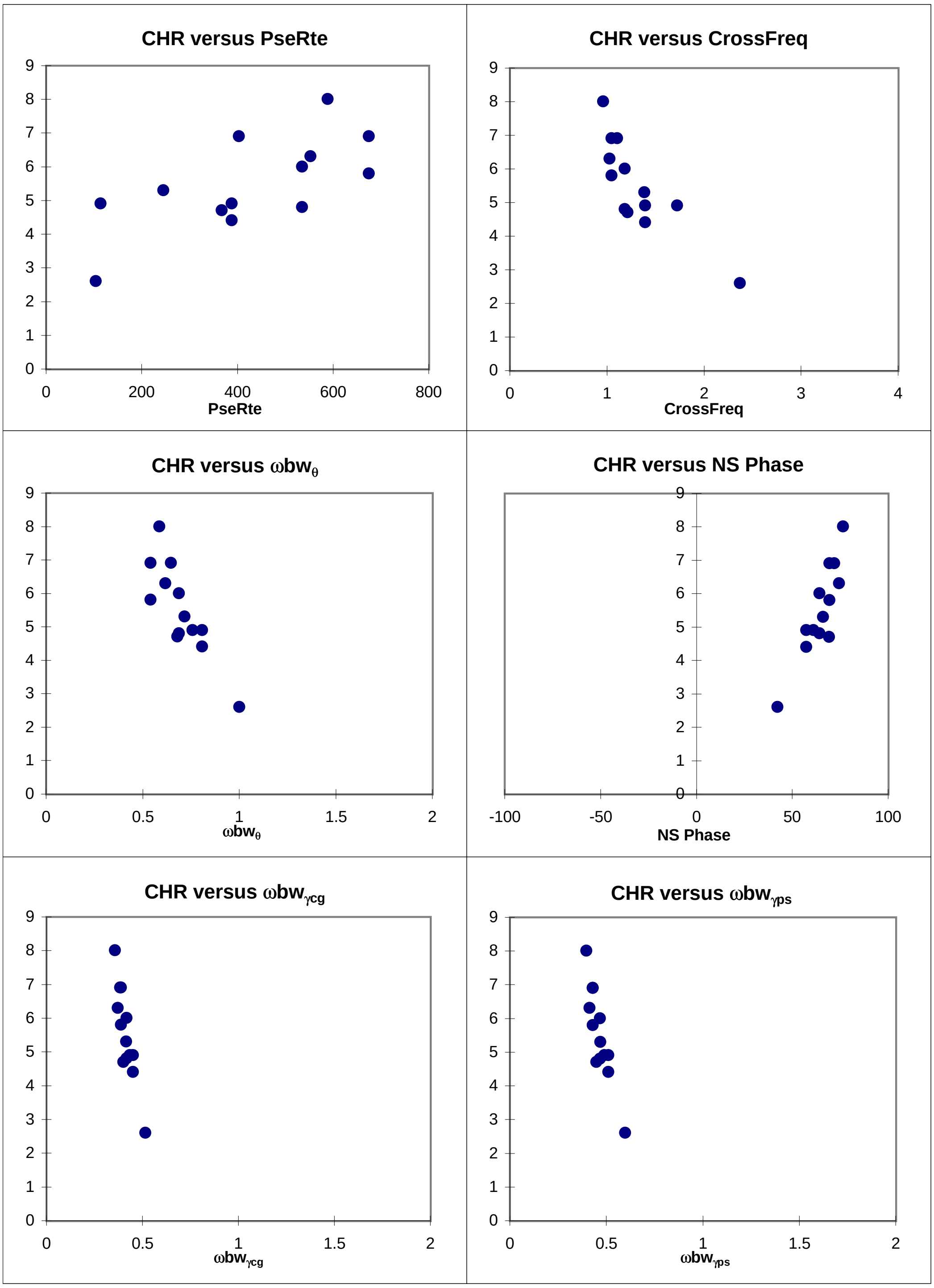


Figure B.18: AIAA 93-3815 Plot Set 2

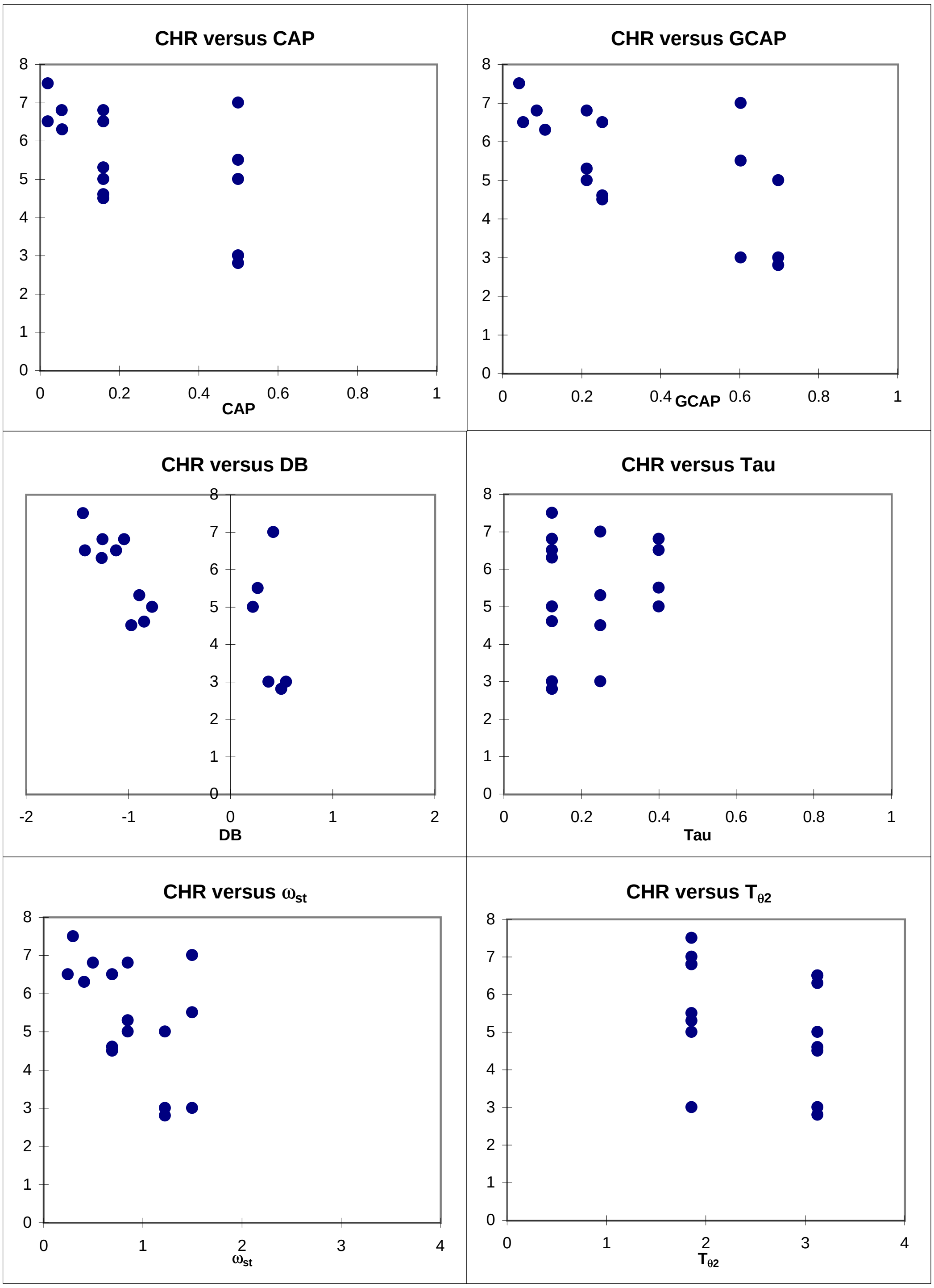


Figure B.19: AIAA 93-3816 Plot Set 1

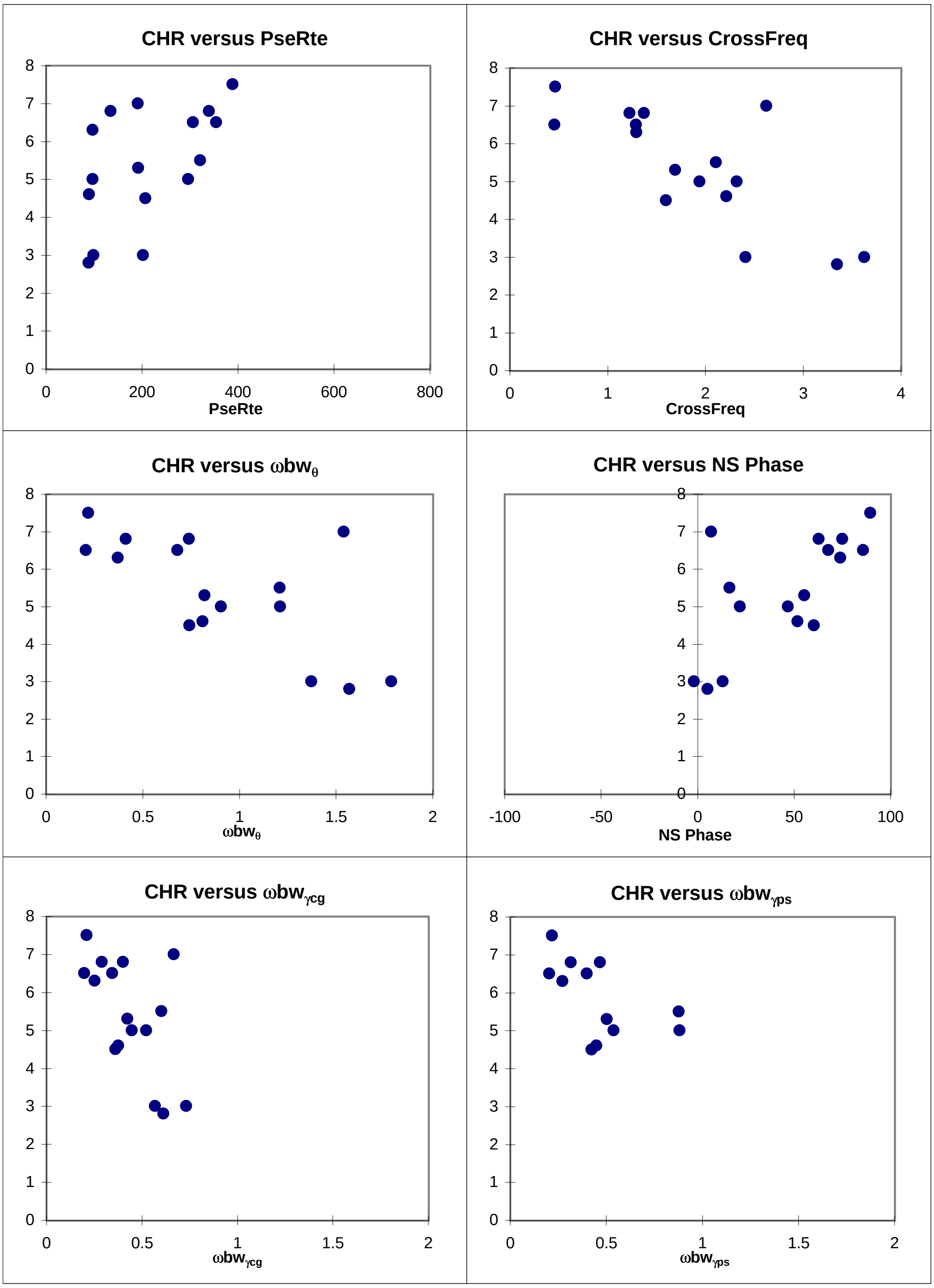


Figure B.20: AIAA 93-3816 Plot Set 2

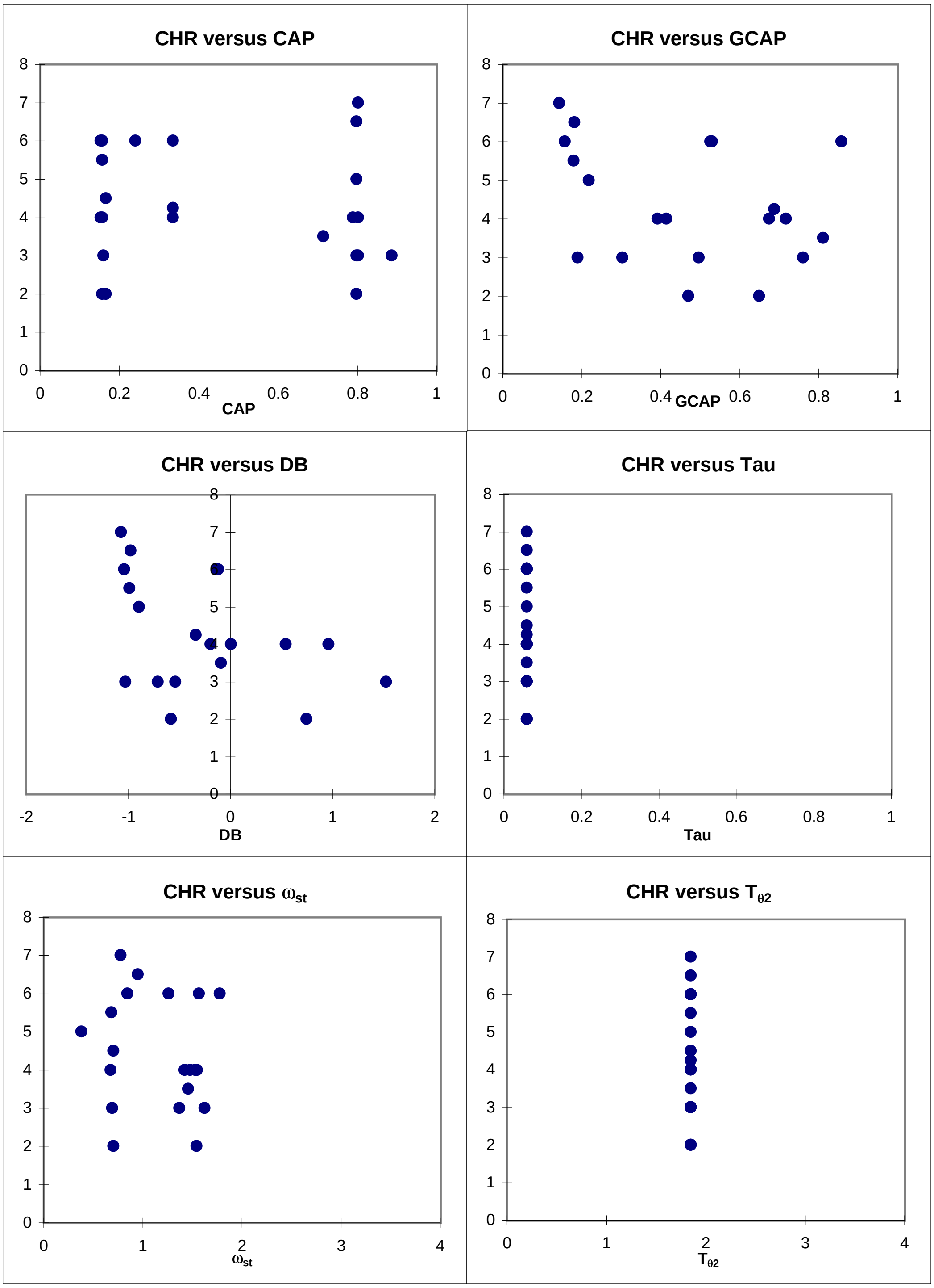


Figure B.21: Field's Thesis Plot Set 1

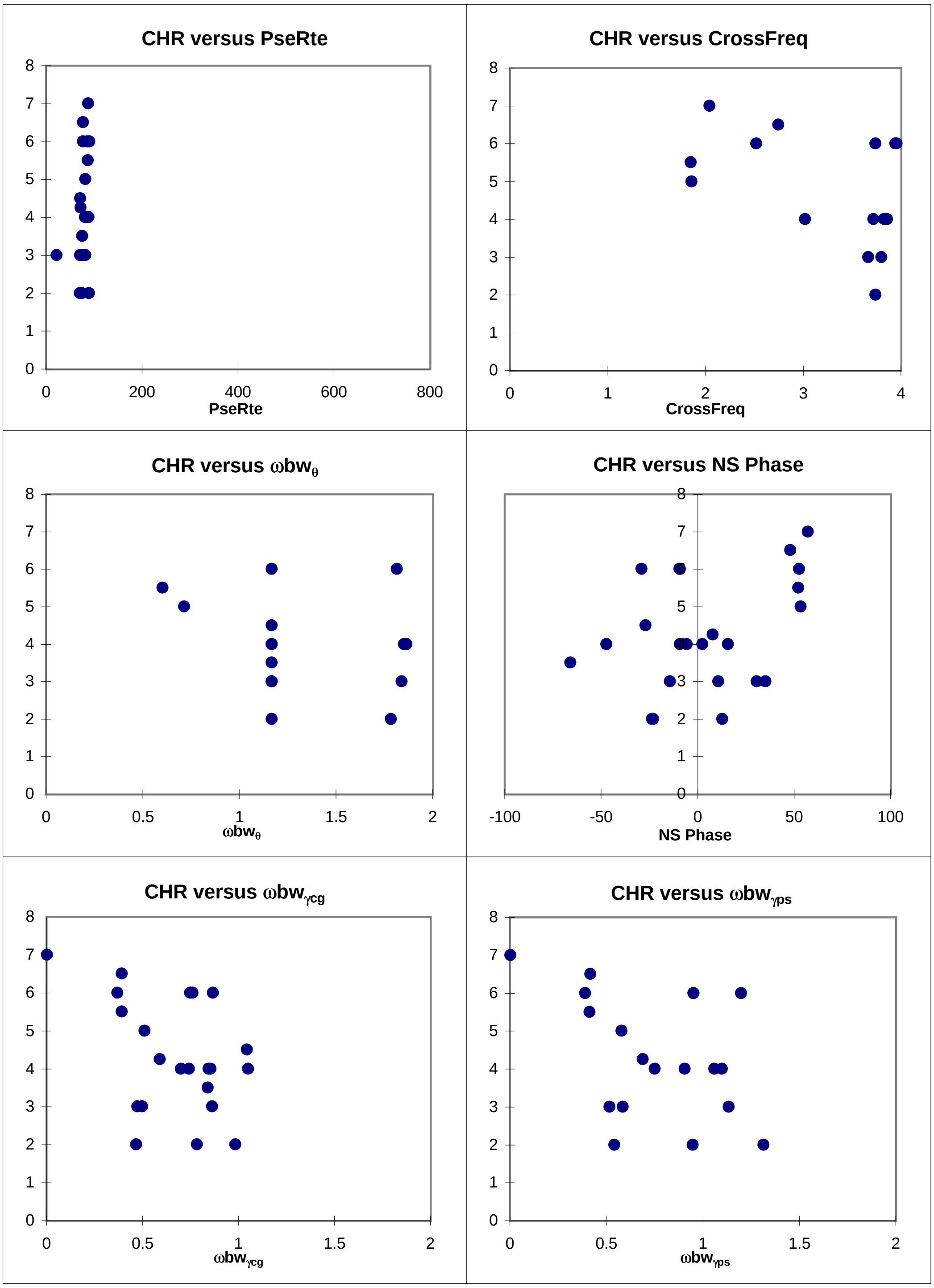


Figure B.22: Field's Thesis Plot Set 2

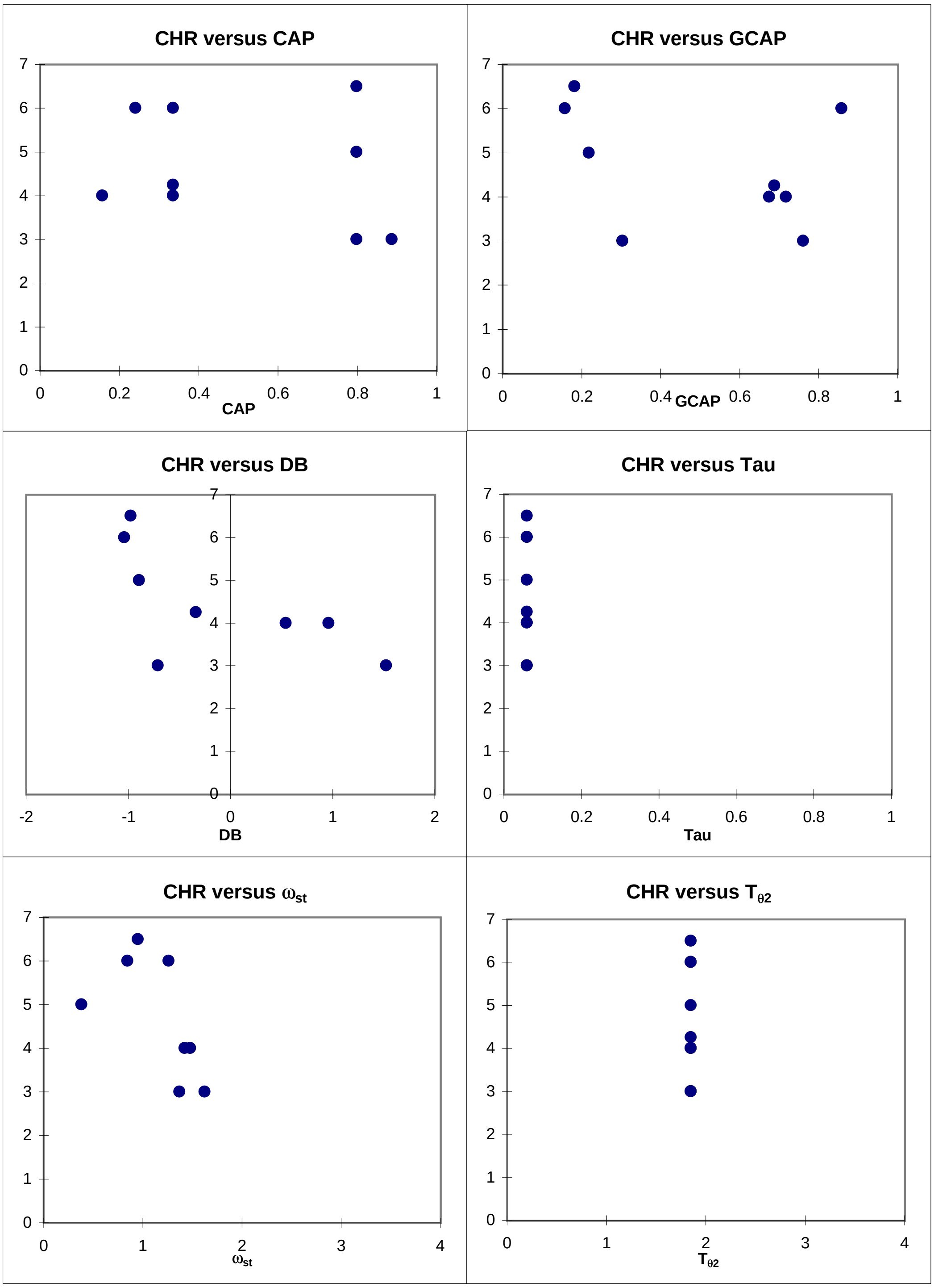


Figure B.23: Field's Thesis ('q' Laws) Plot Set 1

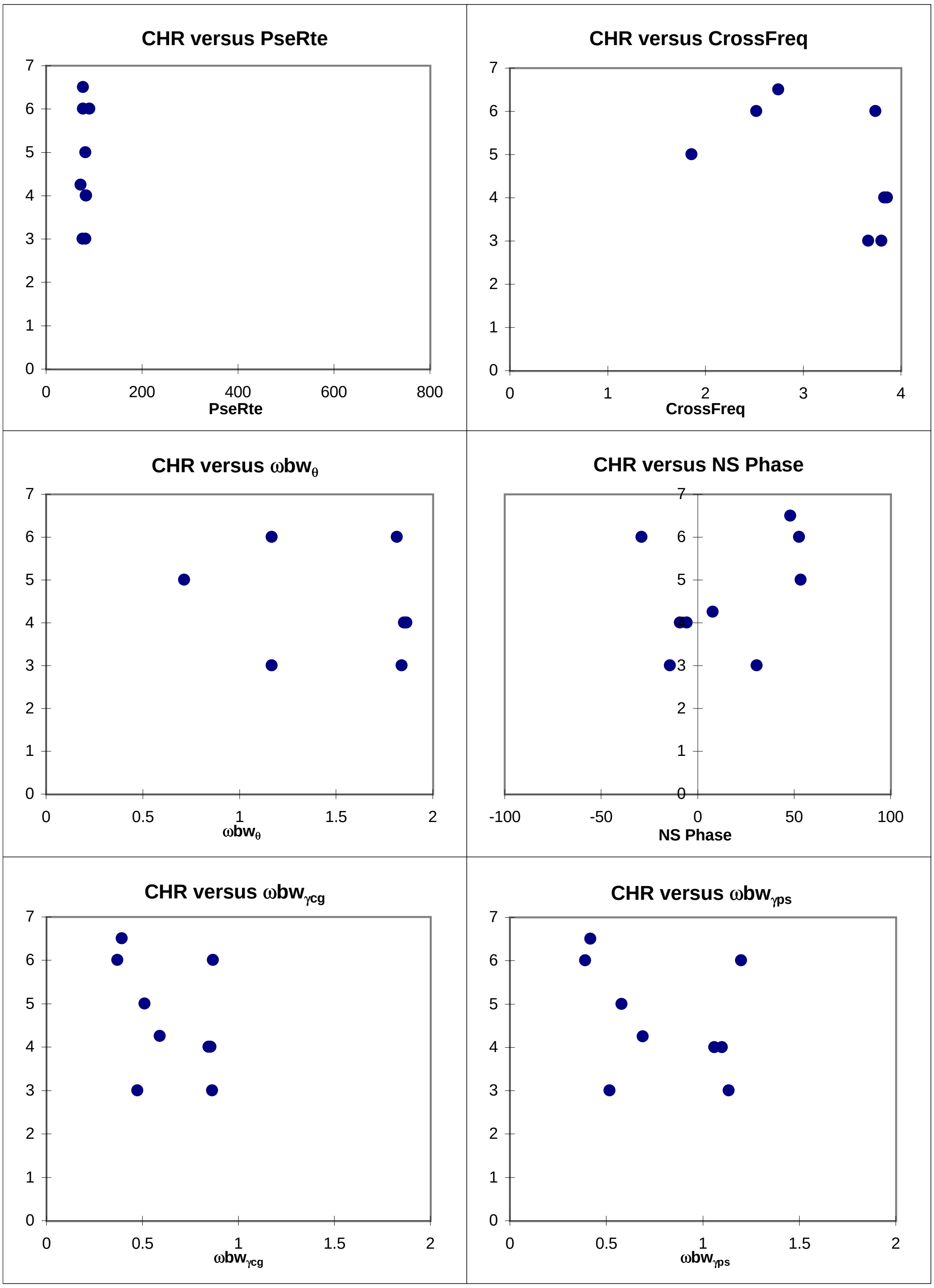


Figure B.24: Field's Thesis ('q' Laws) Plot Set 2

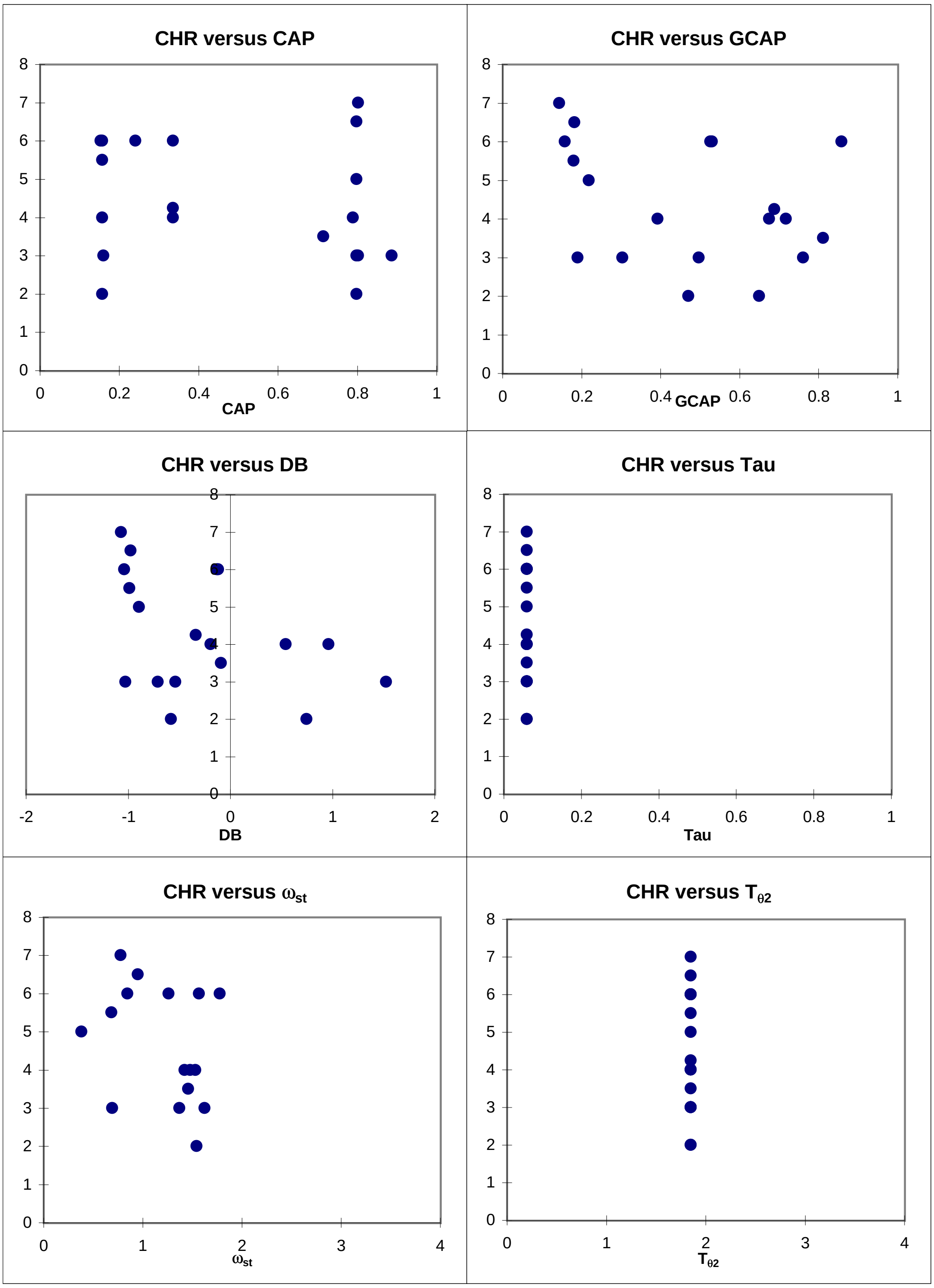


Figure B.25: Field's Thesis (Rate Laws) Plot Set 1

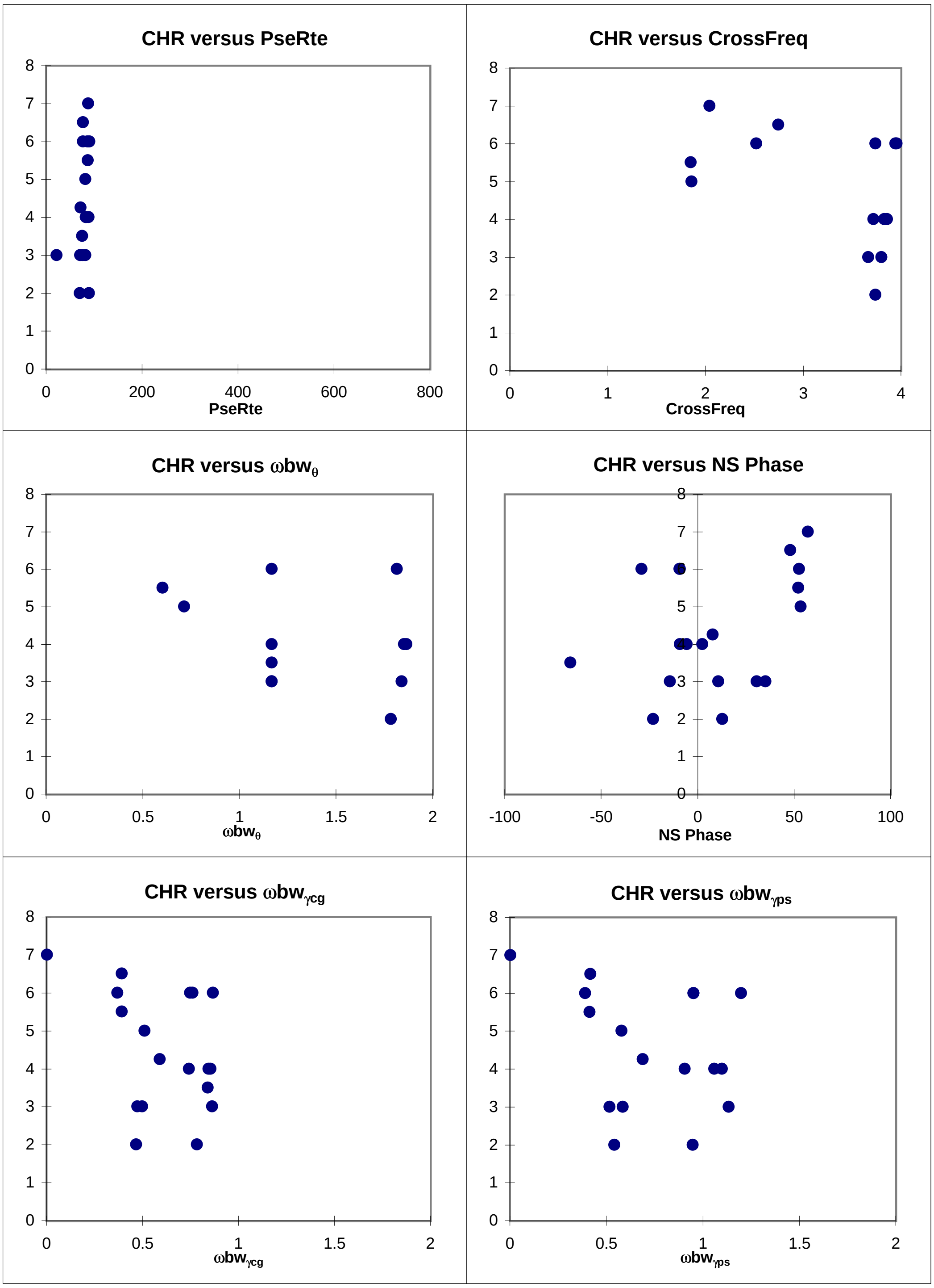


Figure B.26: Field's Thesis (Rate Laws) Plot Set 2

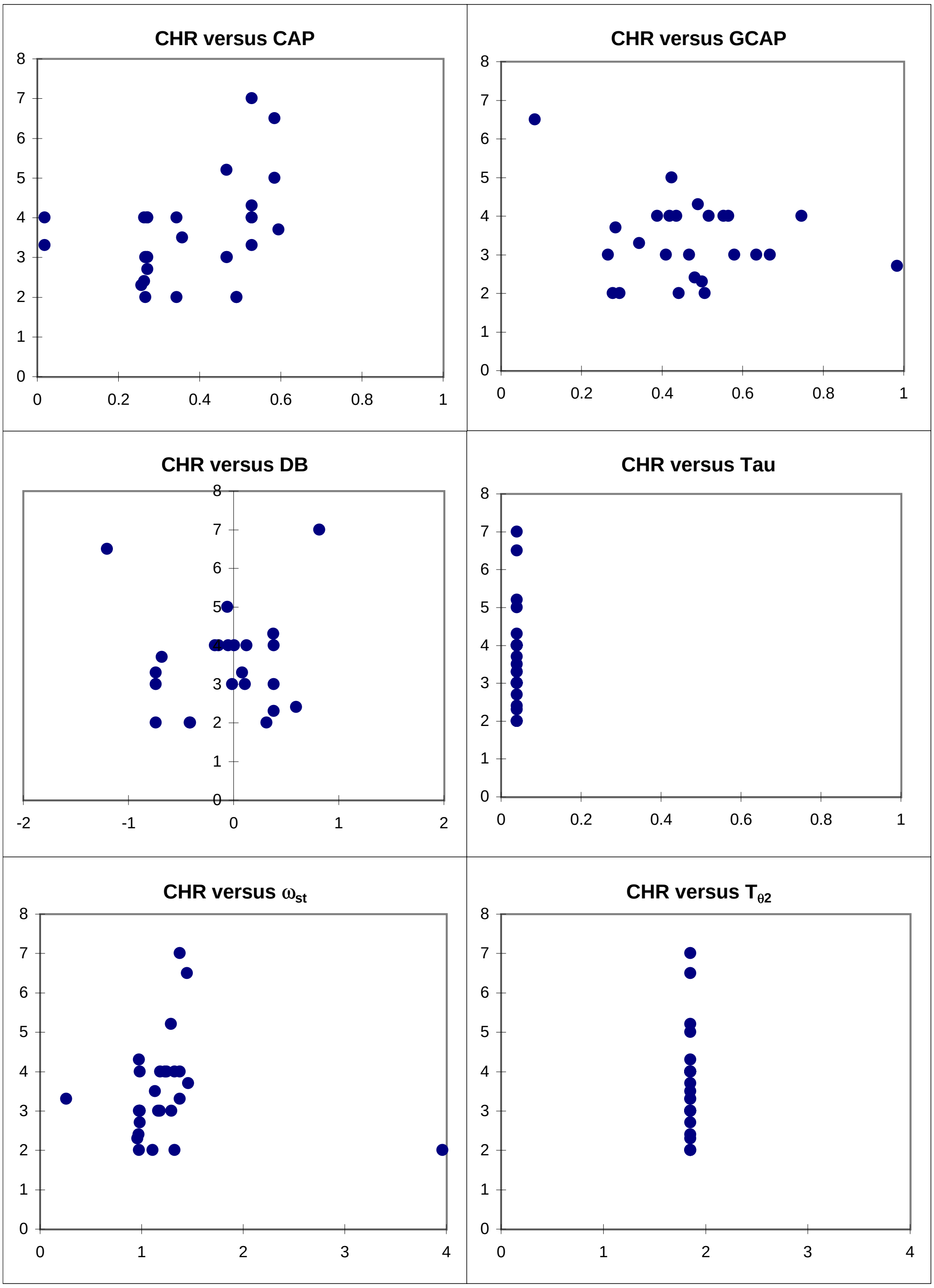


Figure B.27: Field's CoA 9401 Plot Set 1

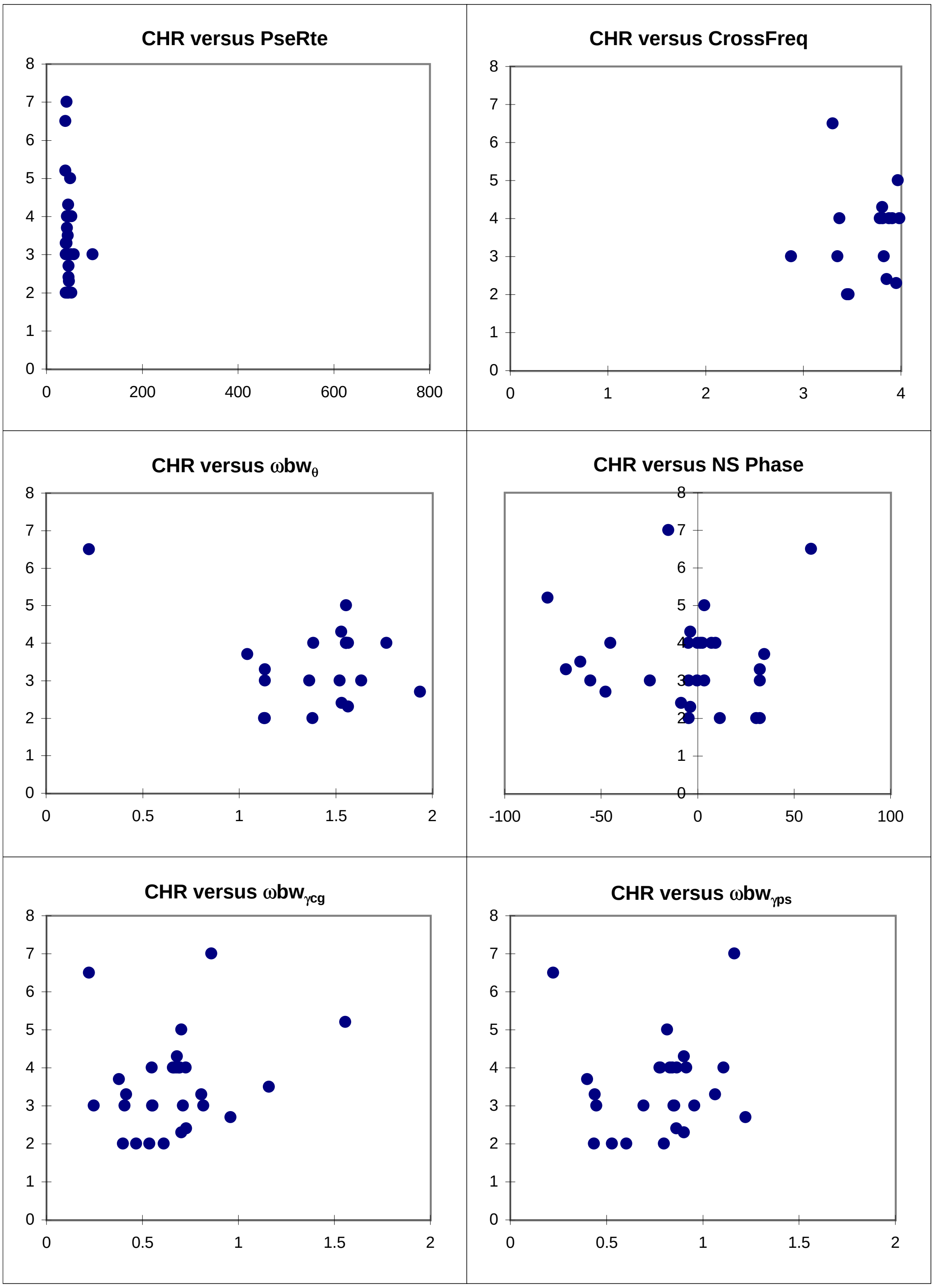


Figure B.28: Field's CoA 9401 Plot Set 2

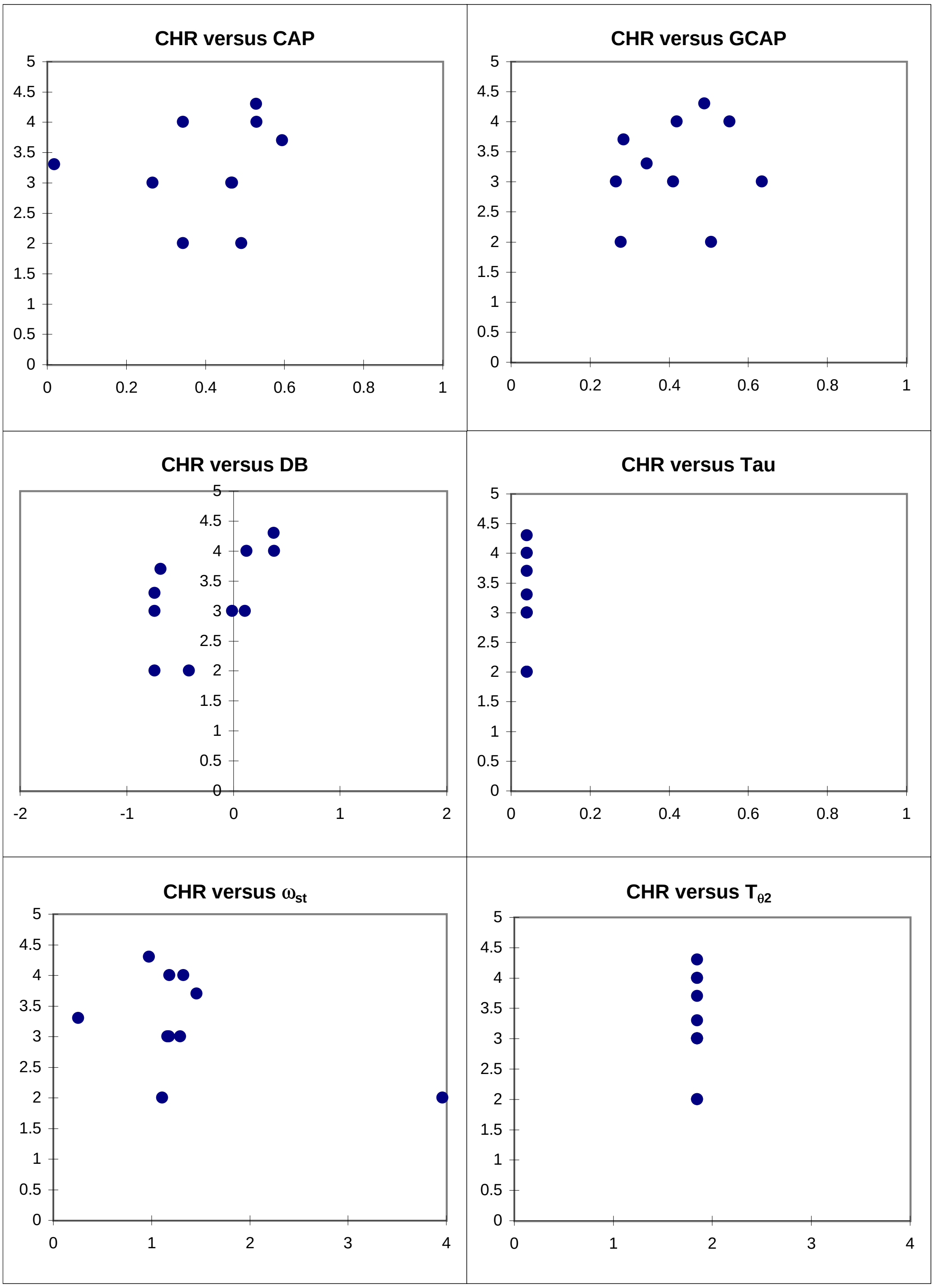


Figure B.29: Field's CoA 9401 ('q' Laws) Plot Set 1

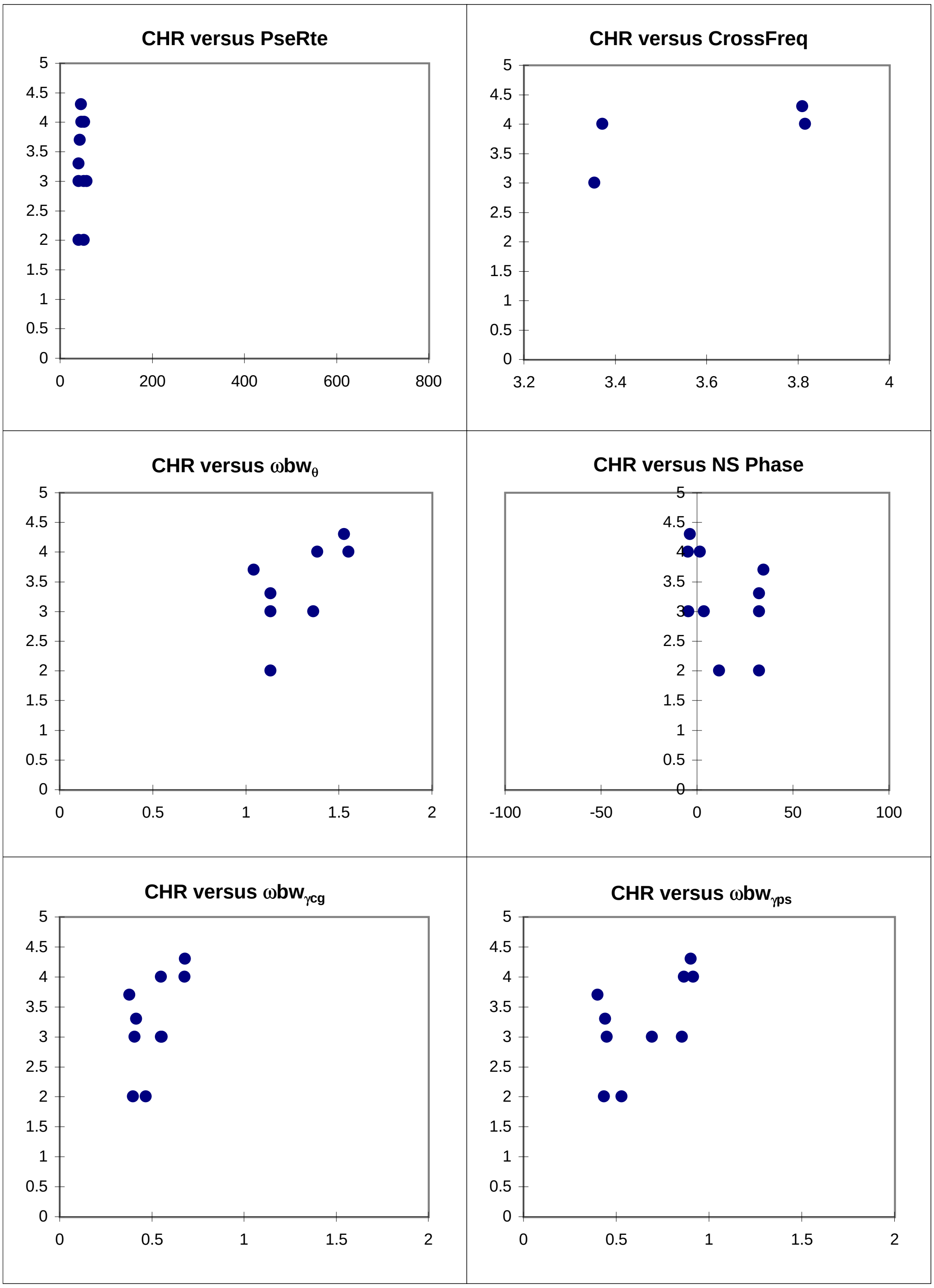


Figure B.30: Field's CoA 9401 ('q' Laws) Plot Set 2

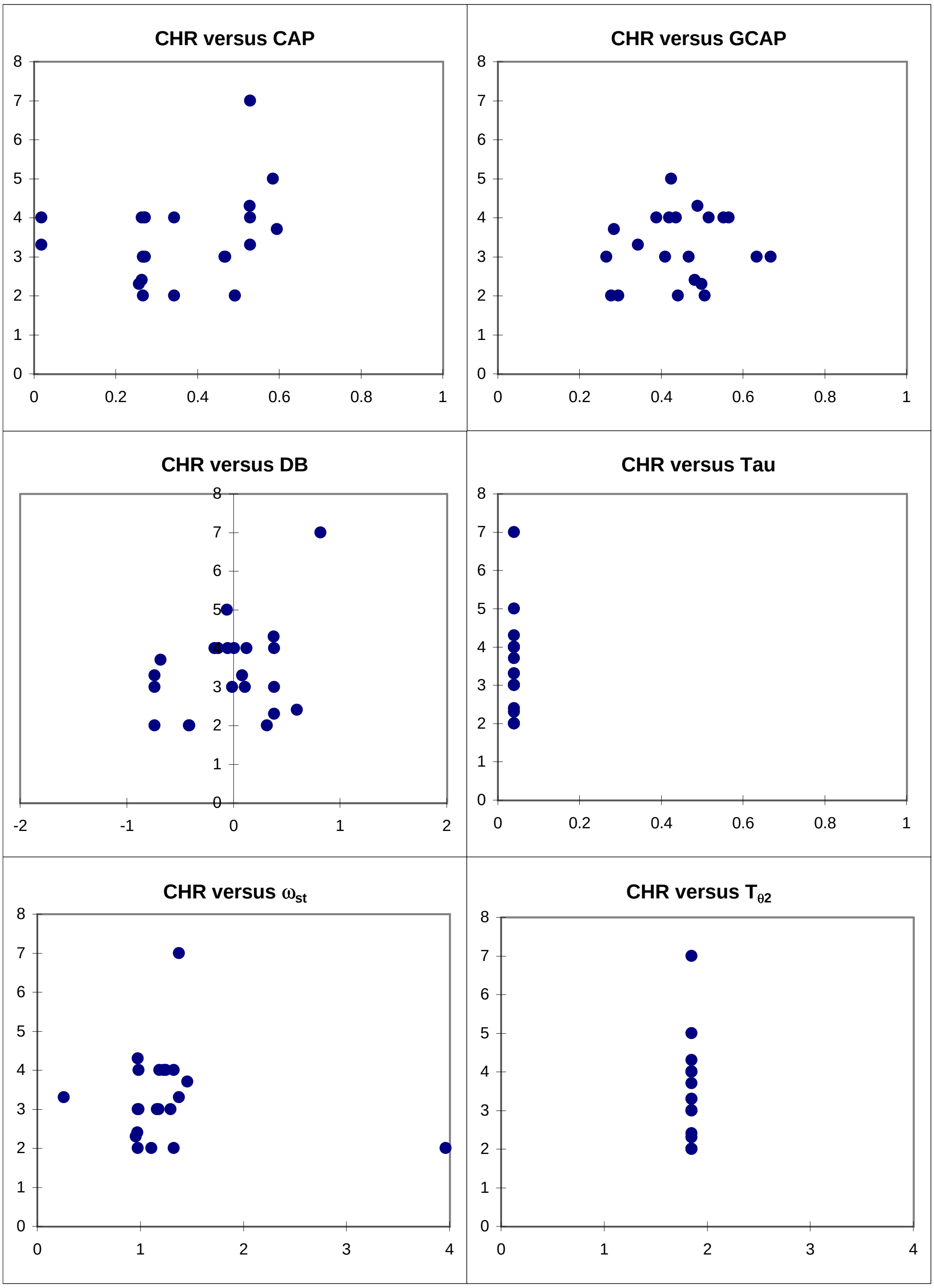


Figure B.31: Field's CoA 9401 (Rate Laws) Plot Set 1

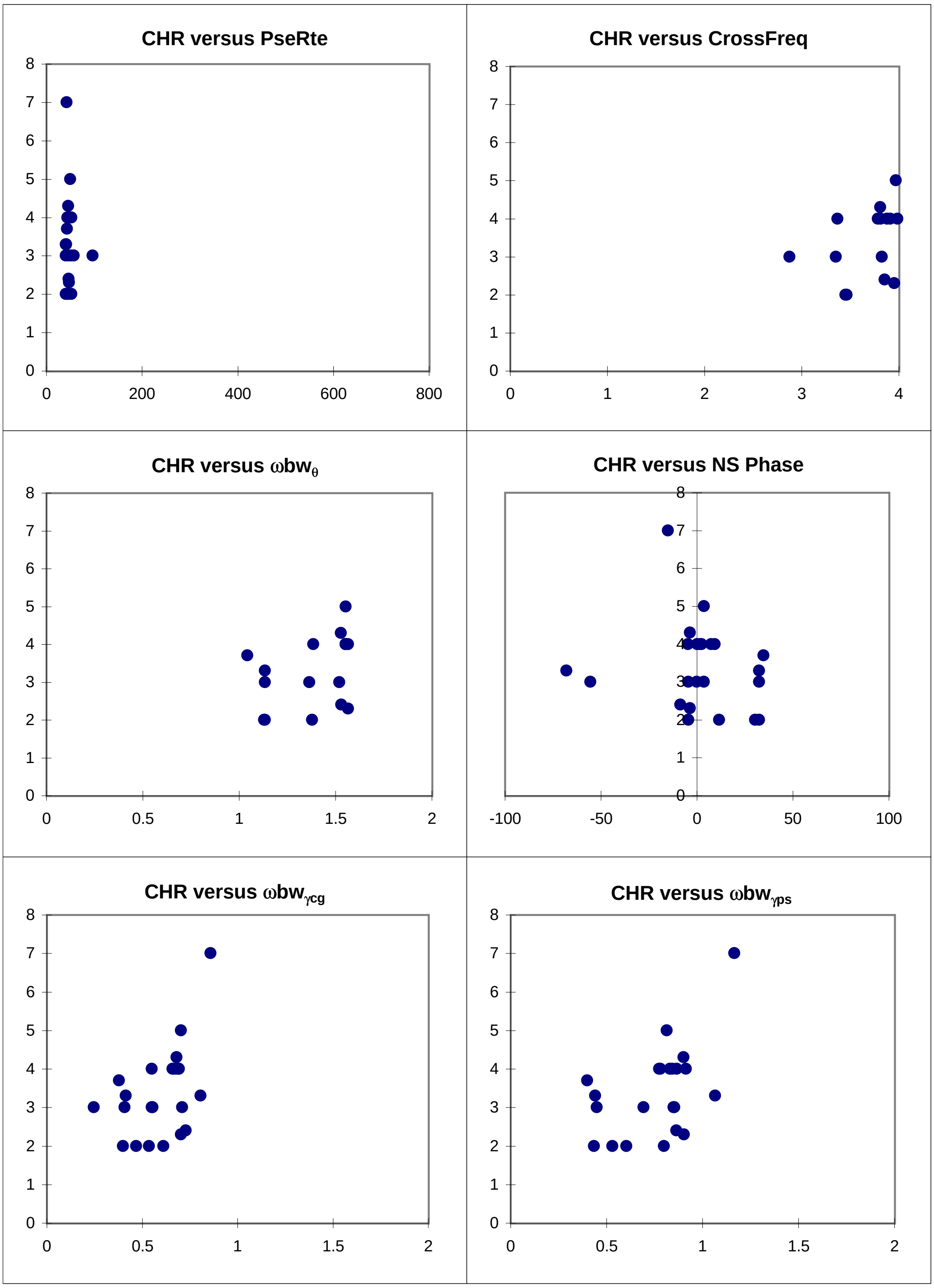


Figure B.32: Field's CoA 9401 (Rate Laws) Plot Set 2

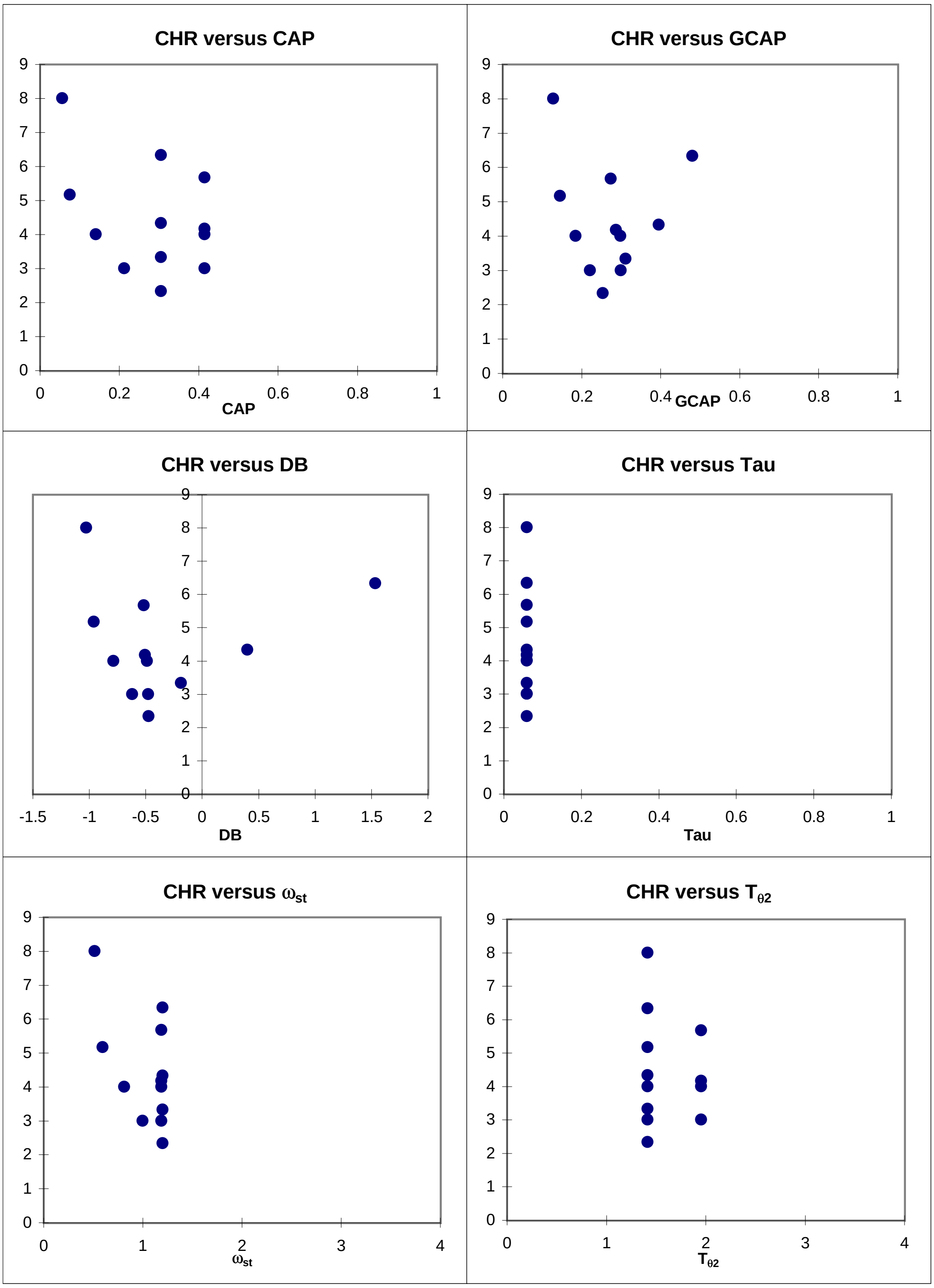


Figure B.33: Mooij VMS Plot Set 1

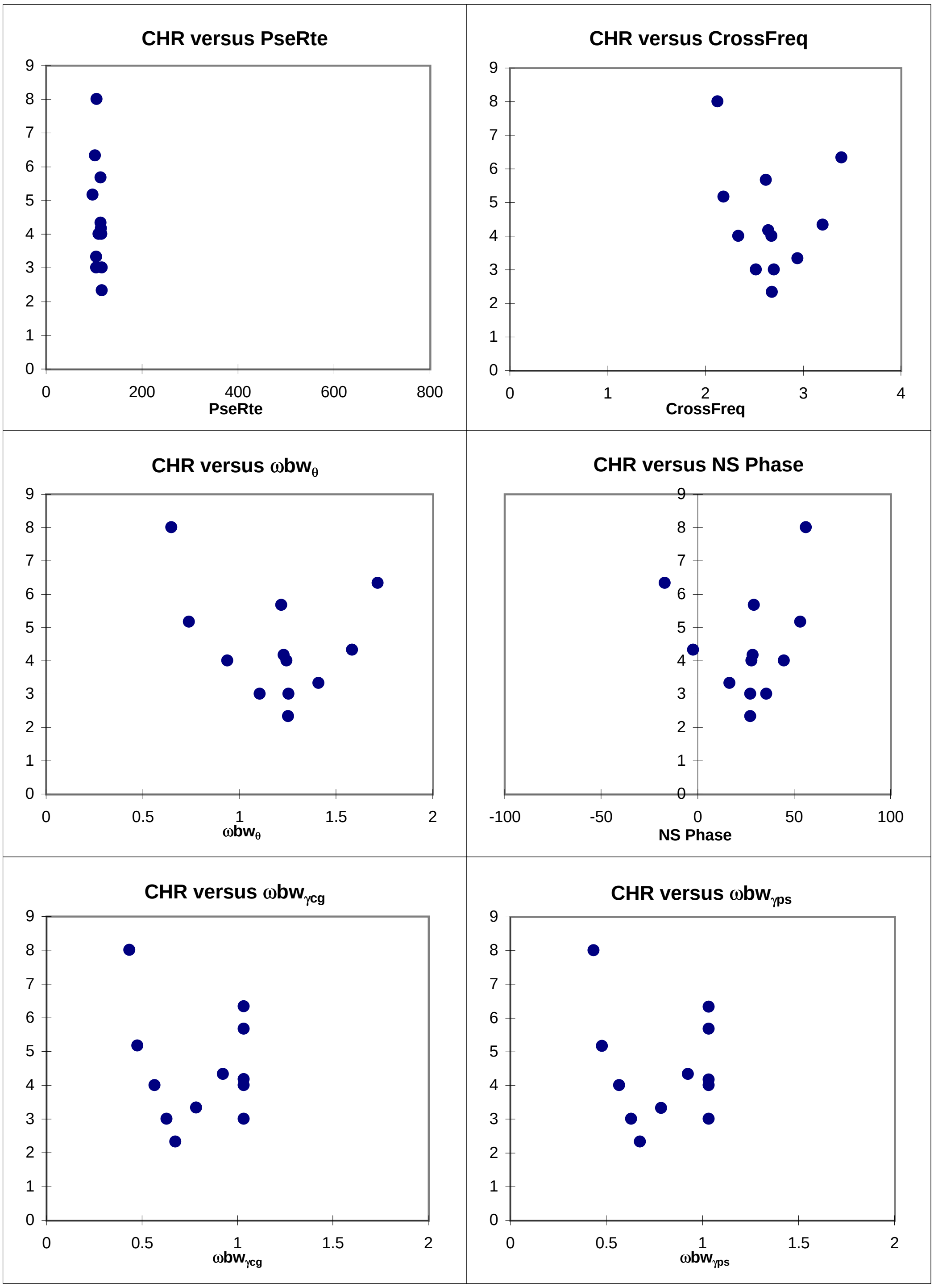


Figure B.34: Mooij VMS Plot Set 2

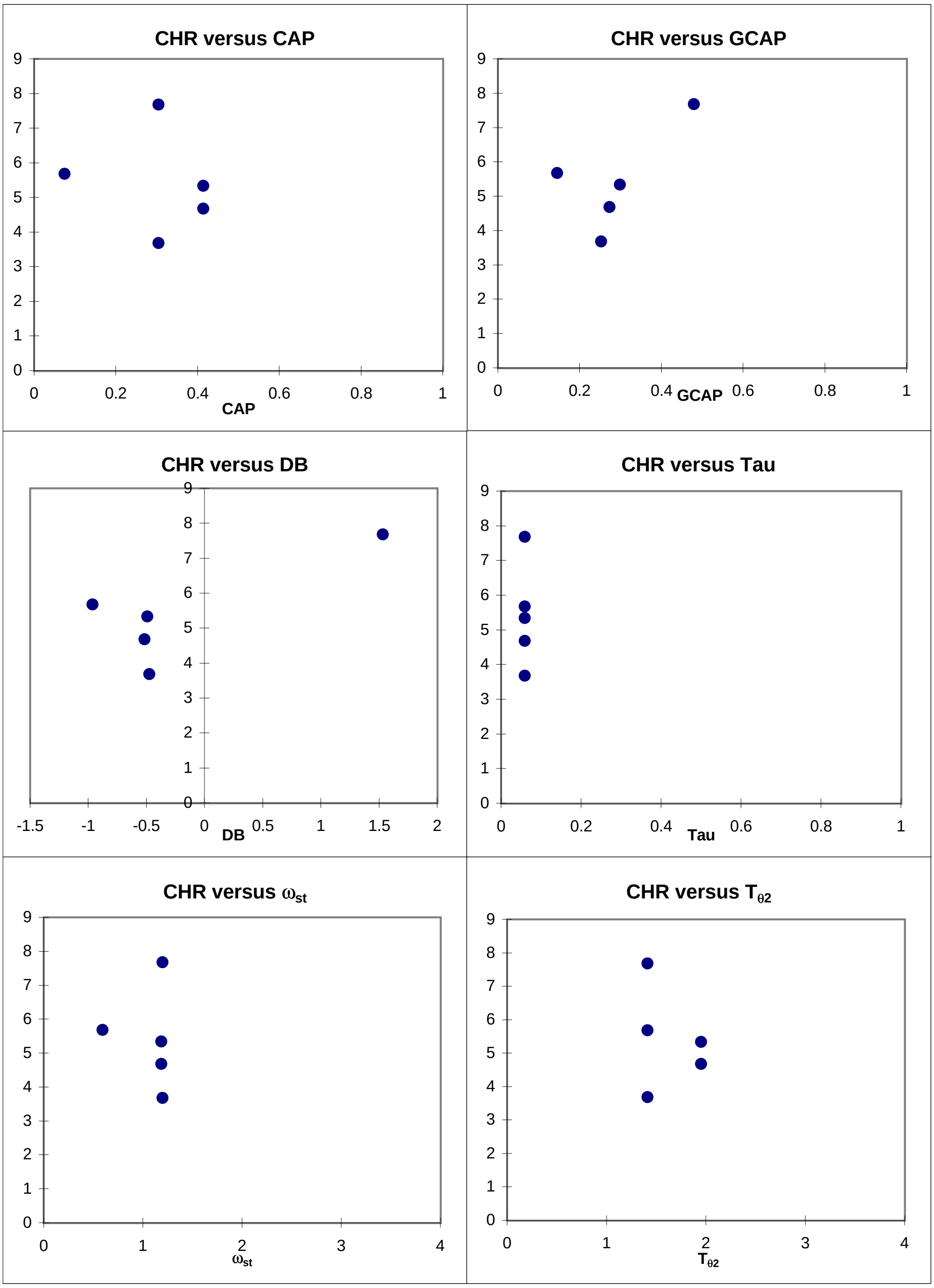


Figure B.35: Mooij TIFS Plot Set 1

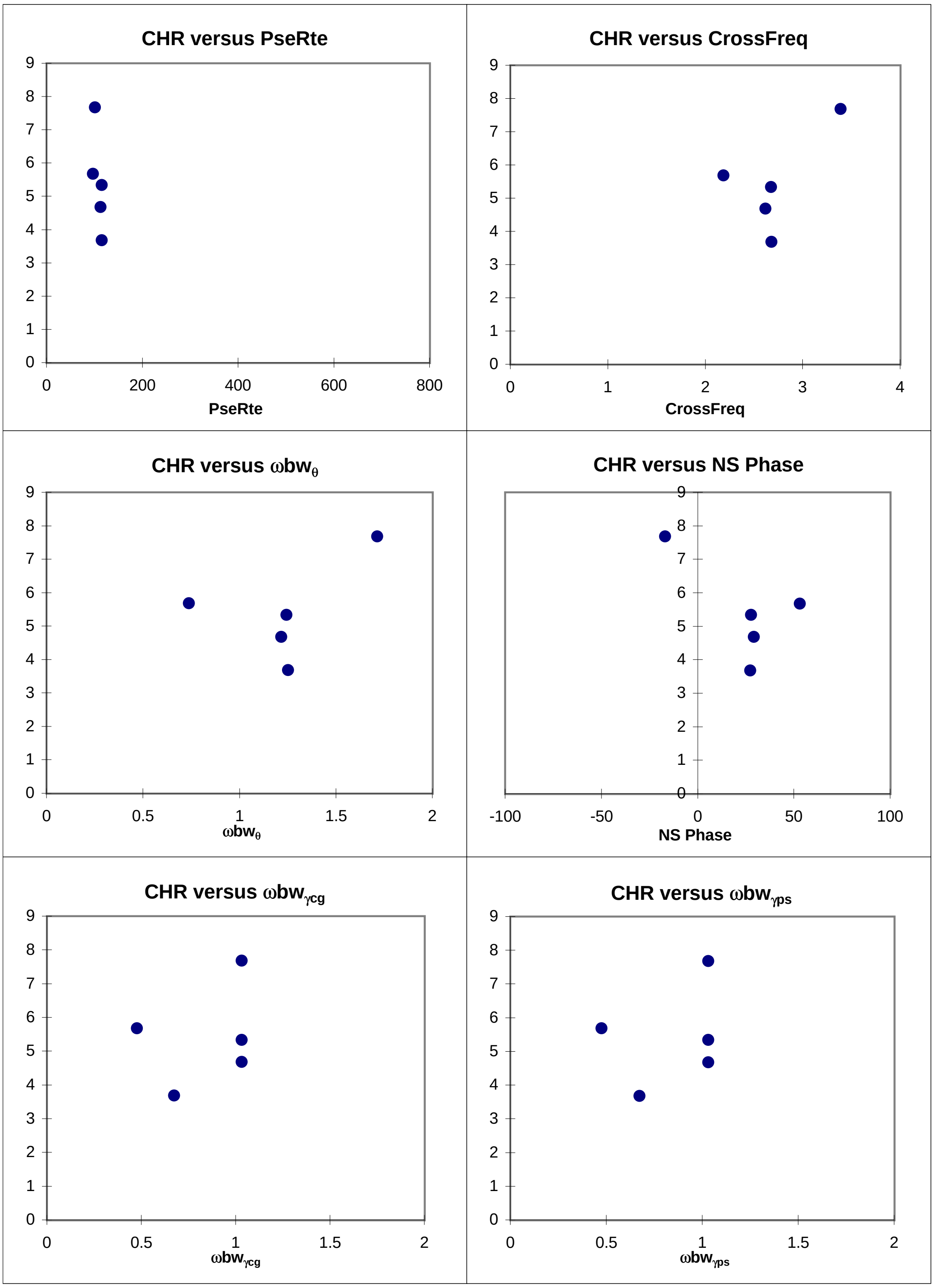


Figure B.36: Mooij TIFS Plot Set 2

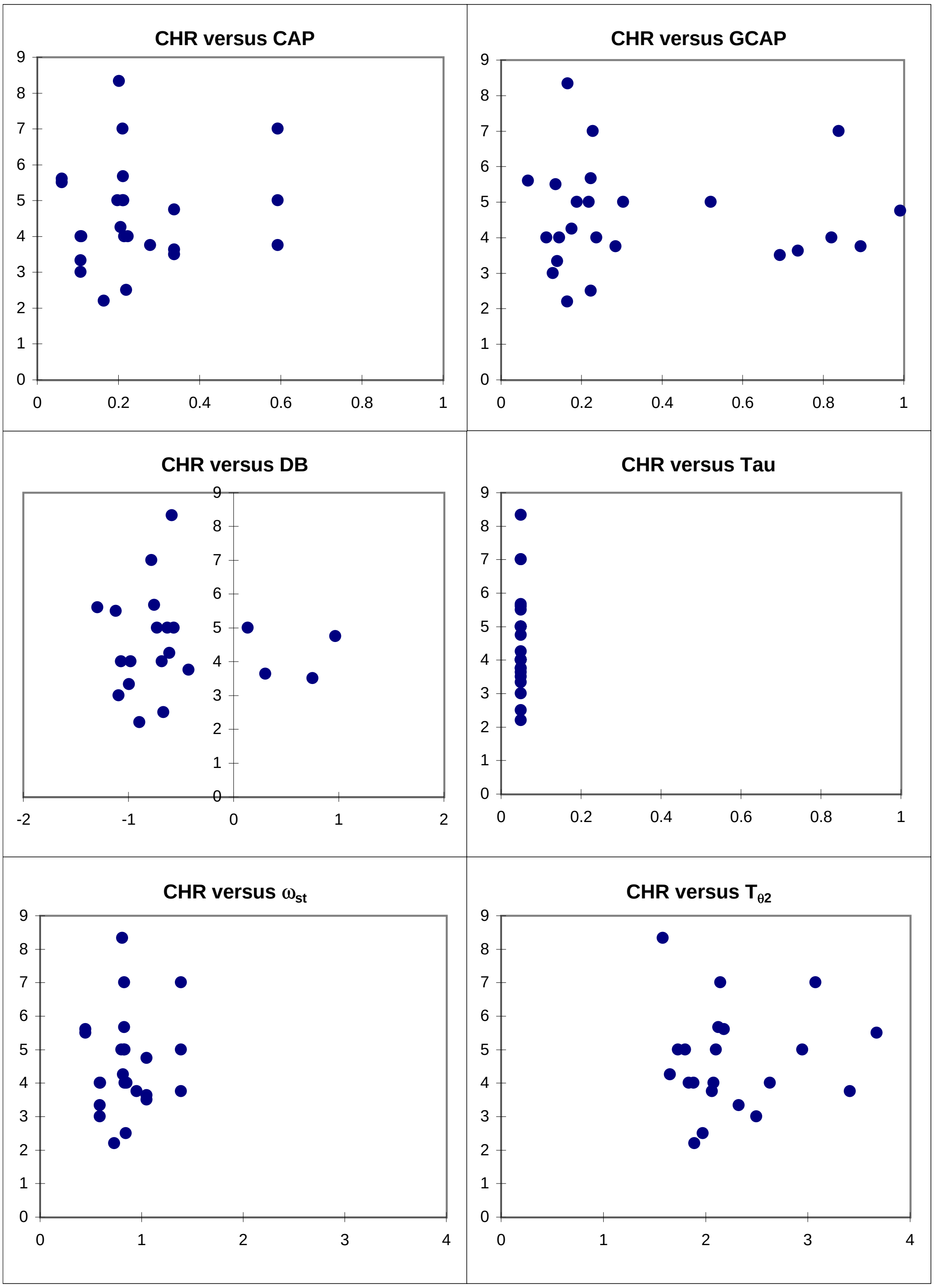


Figure B.37: NASA TR 80-3067 Plot Set 1

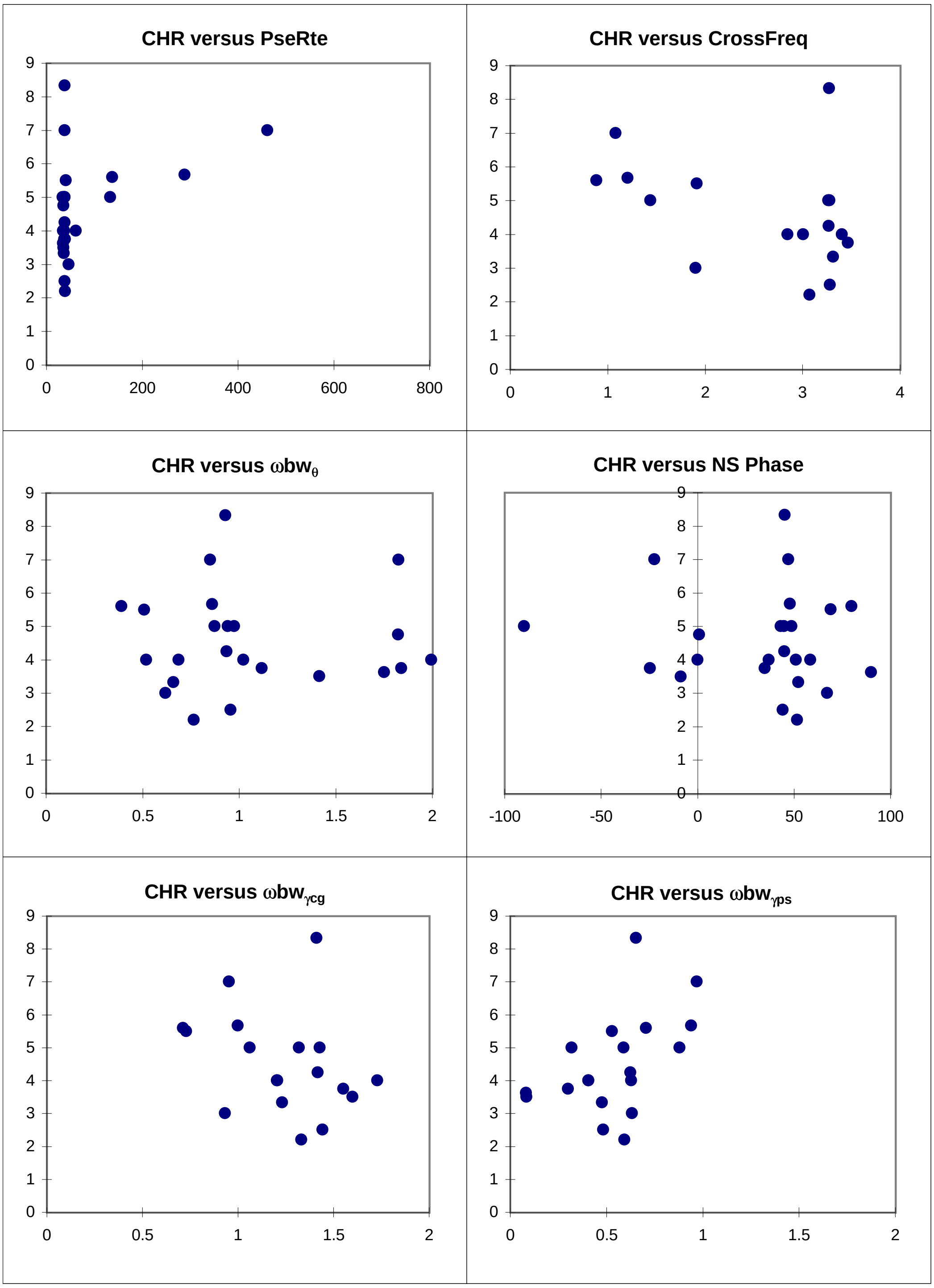


Figure B.38: NASA TR 80-3067 Plot Set 2

C Results of the Evaluation of a Reconfiguration and ILS Approach Tasks

C.1 Evaluation 1 Pilot Comment Card

Pilot Comment Card

Date : Eval No. : Law : Pilot :

Reconfiguration

Response characteristics

Control forces during the reconfiguration

Trimming characteristics

Approach + Landing

Force versus initial pitch acceleration

Force versus achieved pitch rate

Pitch acceleration / pitch rate consonance

Control wheel force / displacement

Trim characteristics

Ability to achieve the desired pitch corrections on the glideslope

Pitch attitude / flight path consonance

Airspeed control

Special piloting techniques

Offset correction

Flare and Touchdown

Control forces

Flare characteristics

Control of touchdown parameters

Technique used

General comments

Lateral / directional effects

Most positive feature of this configuration

Most objectionable feature of this configuration

Initial Overall Impression

Cooper Harper Ratings

Reconfiguration	
Approach	
Flare	
Overall	

Bedford

Reconfiguration	
Approach	

Pilot Induced Oscillation Rating	

Autothrottle

Effects of the autothrottle

Speed / energy awareness

Trimming characteristics

Desirable / undesirable characteristics

Modification in piloting technique due to autothrottle

Cooper Harper Ratings

Reconfiguration	
Approach	
Flare	
Overall	

Bedford

Reconfiguration	
Approach	

Pilot Induced Oscillation Rating	

Unaugmented

(from the point of view of a new line pilot who has just undergone type conversion, who will be flying the aircraft principally on autothrottle, and who has no other heavy experience).

Flyable with current aircraft / control law type

Identify the major problems

Effect of different trimming / autothrottle concept

C.2 Flying Qualities Evaluations Results

Cooper Harper Rating Tables

The Cooper Harper ratings for the reconfiguration, approach, flare and an overall rating can be found in tables C.1 to C.8.

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	4	3	4	4	4
1	3				
2	4	4			4
3	2			3	2.5
4	3				
5	3	3	3		3
6	2,2	3	1	1.5	2
7	2				
8	4				
9	2			4	3
10	4				

Table C.1: Reconfiguration Cooper Harper Ratings without Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	4	4	4	4
1	2				
2	2	4			3
3	1			2.5	1.75
4	2	3	3		3
5		3			
6	2,1	4	1	1.5	1.5
7	1				
8	3				
9	2			4	3
10	3				

Table C.2: Reconfiguration Cooper Harper Ratings with Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	4	3	4	3.5
1	3				
2	4	2			3
3	2			3	2.5
4	3				
5	2	3	3		3
6	2,2	2	2	2.5	2
7	3				
8	4				
9	3			4	3.5
10	4				

Table C.3: Approach Cooper Harper Ratings without Autothrottle

Touchdown Performance

The touchdown performance data can be found in table C.9 and C.11. The data can also be found on figures C.1 to C.6.

Code	Meaning
Eval	Evaluation Number (unique to this law / pilot).
Type	Approach type.
famil	Familiarisation approach.
1 app	1st manual throttle approach.
1 athr	1st autothrottle approach.
base	Baseline.
V_{50}	Airspeed at 50 feet (knots).
V_{td}	Airspeed at touchdown (knots).
$\dot{H}_{50}$	Sink rate at 50 feet (feet per second).
$\dot{H}_{td}$	Sink rate at touchdown (feet per second).
X_{td}	X position on runway at touchdown (feet).
Y_{td}	Y position on runway at touchdown (feet).

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	2	4	4	4.5	4
1	2				
2	4	2			3
3	2			2	2
4	2				
5	2	2	3		2
6	2,2	4	2	1.5	2
7	2				
8	4				
9	4			3	3.5
10	3				

Table C.4: Approach Cooper Harper Ratings with Autothrottle

Bedford Workload Ratings

The Bedford Workload ratings for the reconfiguration and approach for both non-autothrottle and autothrottle aircraft can be found in tables C.12 to C.15. The data is also plotted on figures C.15 to C.18.

PIO Ratings

The overall PIO ratings for both non-autothrottle and autothrottle aircraft can be found in tables C.16 and C.17. The data is also plotted on figures C.19 to C.20.

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	2	2	3	2.5
1	2				
2	3	2			2.5
3	3			2	2.5
4	3				
5	2	2	4		2
6	3,3	2	2	2	2
7	2				
8	6				
9	2			3	2.5
10	2				

Table C.5: Flare Cooper Harper Ratings without Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	4	2	4	3.5
1	2				
2	5	2			3.5
3	3			2	2.5
4	3				
5	2	2	4		2
6	4,2	2	2	1.5	2
7	2				
8	6				
9	4			2	3
10	2				

Table C.6: Flare Cooper Harper Ratings with Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	4	3	4	3.5
1	3				
2	4	2			3
3	3			3	3
4	3				
5	2	3	3		3
6	2,3	3	2	2.5	2.5
7	3				
8	5				
9	3			4	3.5
10	3				

Table C.7: Overall Cooper Harper Ratings without Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	2.5	4	3	4	3.5
1	2				
2	3	2			2.5
3	2			2.5	2.25
4	2				
5	2	2	3		2
6	3,2	4	2	1.5	2
7	2				
8	5				
9	3			3	3
10	3				

Table C.8: Overall Cooper Harper Ratings with Autothrottle

Pilot	Law	Eval	Type	V_{50}	$\dot{H}_{50}$	V_{td}	$\dot{H}_{td}$	X_{td}	Y_{td}
A	0	1	2 app	118.0	10.1	113.2	7.3	95.5	-5.2
A	0	1	1 athr	121.1	12.2	118.5	3.8	-105.4	6.3
A	0	1	2 athr	121.2	10.2	118.9	4.6	56.0	1.0
A	6	2	famil	118.2	9.4	112.0	4.3	55.3	3.1
A	6	2	1 app	118.3	9.7	112.0	5.3	223.0	0.3
A	6	2	1 athr	121.1	13.1	113.9	2.2	79.6	7.7
A	0	2	base	116.7	10.1	111.7	7.5	-76.5	-4.1
A	9	3	famil	120.1	11.2	113.2	4.5	220.7	-1.9
A	9	3	1 app	120.0	9.0	114.7	3.3	39.2	7.9
A	9	3	1 athr	121.1	11.0	117.0	6.1	113.9	-3.4
A	9	3	1 athr	120.9	7.5	116.2	7.5	-0.9	3.8
A	0	3	base	119.1	10.2	116.0	4.3	-143.1	11.7
A	3	4	famil	118.5	12.3	113.5	4.9	-42.9	-0.7
A	3	4	1 app	120.0	11.2	113.3	4.3	125.7	3.2
A	3	4	1 athr	121.3	14.6	114.1	1.5	219.9	0.2
A	3	4	2 athr	121.2	12.5	115.3	3.1	-128.2	-0.6
A	0	4	base	120.5	10.1	115.4	3.0	-19.6	-1.2
A	1	5	famil	118.8	8.1	113.7	6.1	88.1	3.9
A	1	5	1 app	117.5	8.4	112.2	5.8	194.5	3.5
A	1	5	1 athr	121.2	10.6	114.7	3.6	-22.5	1.4
A	6	6	famil	118.3	7.2	110.9	6.4	283.3	-0.4
A	6	6	1 app	119.8	9.8	113.8	4.5	-299.1	5.8
A	6	6	1 athr	121.0	9.8	115.6	3.1	20.0	0.9
A	7	7	famil	119.7	11.0	111.1	5.2	236.5	2.9
A	7	7	1 app	120.9	11.0	116.2	3.1	172.8	2.8
A	7	7	1 athr	121.0	10.3	115.8	4.6	54.0	4.8
A	0	7	base	119.0	14.1	114.5	4.4	-4.9	2.8
A	0	19	prac	117.7	11.0	115.4	6.7	-256.0	-3.6
A	0	19	prac	118.5	10.5	112.1	3.2	62.0	9.0
A	10	19	famil	119.5	9.3	113.3	4.0	216.0	-3.3
A	10	19	1 app	122.1	9.0	114.8	1.6	290.0	5.3
A	10	19	2 app	120.9	11.1	112.2	1.0	214.0	9.2
A	10	19	3 app	120.5	8.6	113.3	3.6	235.0	-7.5
A	10	19	1 athr	120.9	9.1	116.3	5.4	217.0	8.2
A	10	19	2 athr	121.0	9.4	116.5	5.1	-158.0	-3.3
A	10	19	3 athr	121.1	12.0	112.6	1.4	242.0	5.5
A	5	20	famil	118.9	9.7	110.1	2.3	97.0	9.8
A	5	20	1 app	120.9	8.7	113.0	3.6	173.0	11.6
A	5	20	1 athr	121.3	10.5	114.2	4.6	-7.0	6.0

Table C.9: Touchdown Performance Data (1)

Pilot	Law	Eval	Type	V_{50}	$\dot{H}_{50}$	V_{td}	$\dot{H}_{td}$	X_{td}	Y_{td}
A	2	21	famil	120.0	9.5	112.4	4.8	12.0	-0.5
A	2	21	1 app	119.6	7.8	113.6	4.0	9.0	11.1
A	2	21	1 athr	121.4	9.9	112.9	5.9	121.0	2.1
A	2	21	2 athr	120.9	11.0	101.1	3.3	957.0	5.3
A	2	21	3 athr	121.0	10.8	113.3	3.8	-174.0	0.4
A	8	22	famil	121.4	9.9	106.8	3.4	528.0	8.7
A	8	22	1 app	121.0	5.9	107.6	1.5	544.0	0.4
A	8	22	1 athr	120.9	8.3	112.3	3.3	230.0	-3.3
A	8	22	2 athr	120.8	9.4	103.2	6.6	859.0	-9.5
A	4	23	famil	120.5	9.4	113.8	3.4	-102.0	3.9
A	4	23	1 app	120.8	8.9	113.7	3.1	-31.0	7.1
A	4	23	1 athr	121.1	11.4	103.4	2.8	834.0	7.4
A	4	23	2 athr	120.9	9.1	113.3	2.9	61.0	-4.1
B	0	8	famil	125.0	12.4	118.5	6.4	50.2	0.2
B	0	8	1app	119.8	9.1	116.5	7.1	-12.5	4.9
B	0	8	2app	121.3	11.4	116.9	6.0	-86.5	1.8
B	0	8	1athr	121.1	11.9	119.0	9.7	-145.5	-2.6
B	0	8	2athr	121.1	13.2	117.0	5.2	-82.8	1.0
B	6	9	famil	120.9	10.1	114.9	4.3	107.8	1.0
B	6	9	app1	120.5	7.4	115.8	6.7	73.7	-1.7
B	6	9	athr1	120.9	7.7	115.3	5.5	-41.1	-1.0
B	6	9	athr2	120.8	7.9	114.8	4.4	-5.1	6.6
B	2	10	famil	122.7	9.6	116.4	3.8	324.8	6.8
B	2	10	1app	121.1	10.9	116.1	3.4	120.0	3.8
B	2	10	1athr	120.7	8.4	116.6	6.0	-56.8	6.1
B	2	10	2athr	120.8	7.4	120.0	4.4	40.9	14.8
B	5	11	famil	122.5	13.6	118.2	5.7	123.3	10.9
B	5	11	1app	120.5	9.8	114.7	4.7	2.1	-0.2
B	5	11	1athr	120.7	7.4	116.2	7.4	5.2	5.6
C	0	12	famil	120.0	13.6	115.2	5.9	-216.0	-3.8
C	0	12	1 app	121.7	15.5	117.4	7.2	-195.0	3.2
C	0	12	1 athr	121.2	12.6	117.8	7.9	-183.0	3.5
C	6	13	1 app	111.3	10.4	106.8	5.4	-272.0	1.6
C	6	13	1 athr	120.0	11.3	117.0	9.6	-204.0	0.7
C	5	14	famil	117.5	13.9	114.0	9.1	-245.0	-0.7
C	5	14	1 app	115.7	10.6	109.3	7.0	-273.0	4.2
C	5	14	1 athr	120.6	14.6	116.2	6.2	-226.0	0.0

Table C.10: Touchdown Performance Data (2)

Pilot	Law	Eval	Type	V_{50}	$\dot{H}_{50}$	V_{td}	$\dot{H}_{td}$	X_{td}	Y_{td}
D	0	15	famil	126.8	15.9	123.7	8.3	145.0	0.1
D	0	15	1 app	121.2	11.8	119.2	8.5	47.0	-0.7
D	0	15	2 app	124.0	13.1	120.8	8.8	101.0	1.8
D	0	15	1 athr	121.9	19.9	119.0	8.2	68.0	3.5
D	3	16	famil	122.9	15.8	120.4	9.2	201.0	5.3
D	3	16	1 app	121.2	13.5	117.9	7.8	139.0	2.8
D	3	16	1 athr	121.3	10.4	118.3	8.6	91.0	1.9
D	6	17	famil	126.9	16.3	123.6	7.0	83.0	-2.1
D	6	17	1 app	124.8	11.8	121.1	9.6	169.0	-7.4
D	6	17	1 athr	121.6	13.9	117.4	6.1	-97.0	1.9
D	9	18	1 app	124.1	13.5	120.3	6.3	149.0	2.6
D	9	18	1 athr	121.3	13.8	117.0	7.1	-16.0	0.9

Table C.11: Touchdown Performance Data (3)

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	3	3	3	3
1	3				
2	4	4			4
3	1			2.5	1.75
4	3				
5	3	3	3		3
6	2,2	3	1	1	2
7	2				
8	4				
9	2			4	3
10	4				

Table C.12: Reconfiguration Bedford Ratings without Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	3	4	3	3	3
1	3				
2	4	2			3
3	2			2.5	2.25
4	3				
5	2	3	3		3
6	2,3	2	2	2	2
7	3				
8	4				
9	3			4	3.5
10	4				

Table C.13: Reconfiguration Bedford Ratings with Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	2	4	4	2.5	3.25
1	2				
2	2	4			3
3	1			2.5	1.75
4	2				
5	2	3	3		3
6	1,1	3	1	1	1
7	1				
8	3				
9	2			3	2.5
10	3				

Table C.14: Approach Bedford Ratings without Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	2	4	4	3	3.5
1	2				
2	4	2			3
3	2			2	2
4	2				
5	2	2	2		2
6	1,2	2	2	1	2
7	2				
8	3				
9	3			3	3
10	3				

Table C.15: Approach Bedford Ratings with Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	1	1	1	3	1
1	1				
2	1	1			1
3	1			2	1.5
4	1				
5	1	1	2		1
6	1,1	2	1	2	1
7	1				
8	1				
9	1			2	1.5
10	1				

Table C.16: PIO Ratings without Autothrottle

Law	Pilot A	Pilot B	Pilot C	Pilot D	Median
0	1	2	2.5	4	2.25
1	1				
2	1	1			1
3	1			2	1.5
4	1				
5	1	1	1		1
6	1,1	1	1	2	1
7	1				
8	1				
9	1			2	1.5
10	1				

Table C.17: PIO Ratings with Autothrottle

D Results of the Approach through Windshear and Formation Flying Tasks

D.1 Evaluation 2 Pilot Comment Card

Pilot Comment Card

Date : Eval No. : Law : Pilot :

Approach + Landing

Could you comment on the pitch response characteristics.

Could you comment on the trim characteristics.

Could you comment on the ability to achieve the desired pitch corrections on the glideslope.

Could you comment on the pitch attitude / flight path consonance

Could you comment on the flight path vector display

Could you comment on the airspeed control.

Did you use any special piloting technique ?

Do you have any further comments about the windshear ?

Flare and Touchdown

Could you comment on the control forces.

Could you comment on the flare characteristics.

Could you comment on the control of touchdown parameters.

Could you comment on the technique you used.

General Comments

Could you comment on the lateral / directional control laws.

What was the most positive feature of this configuration ?

What was the most objectionable feature of this configuration ?

What was your initial overall impression ?

Cooper Harper Ratings

Approach - Before Shear	
Approach - During Shear	
Flare	
Overall	

Bedford Workload Rating

Approach - Before Shear	

Pilot Induced Oscillation Rating - Before Shear	
Pilot Induced Oscillation Rating - During Shear	

Current Time	

Pilot Comment Card

Date : Eval No. : Law : Pilot :

Formation

Could you comment on the pitch response characteristics.

Could you comment on the trim characteristics.

Could you comment on the ability to achieve the desired flight path corrections.

Could you comment on the pitch attitude / flight path consonance.

Could you comment on the airspeed control.

Did you use any special piloting technique?

General Comments

Could you comment on the lateral / directional control laws.

What was the most positive feature of this configuration ?

What was the most objectionable feature of this configuration ?

What was your initial overall impression ?

Cooper Harper Ratings	
Bedford	
Pilot Induced Oscillation Rating	
Current Time	

D.2 Flying Qualities Evaluations Results

Cooper Harper Ratings

The Cooper Harper ratings can be found in tables D.1 to D.4 for the approach and landing task.

Law	Pilot A	Pilot E	Median
0	4	3	3.5
1	4	3	3.5
3	3	2	2.5
6	2	2	2
7	2	2	2
10	3	2	2.5

Table D.1: Approach Cooper Harper Ratings

Law	Pilot A	Pilot E	Median
0	5	6	5.5
1	5	6	5.5
3	5	5	5
6	3	3	3
7	4	4	4
10	4	3	3.5

Table D.2: Shear Cooper Harper Ratings

Approach segment Cranfield Handling Qualities Rating

The Cranfield Handling Qualities Rating scale results for the approach segment of the windshear task can be found in table D.5.

Bedford Workload Ratings

The Bedford workload ratings can be found in table D.2 for the approach segment.

Law	Pilot A
0	6
1	3
3	3
6	3
7	5
10	3

Table D.3: Flare Cooper Harper Ratings

Law	Pilot A
0	5
1	4
3	4
6	3
7	4
10	3

Table D.4: Overall Cooper Harper Ratings

PIO Ratings

The overall PIO ratings for the approach segment of the windshear task can be found in table D.2.

Touchdown Data

The touchdown data for the approach and landing task can be found in table D.8.

Formation Task Results

This section contains the results from the formation flying task.

Law	Long Char	Lat Char	Dir Char	Trim	Speed	CFDHQR
Weighting	4	4	3	3	4	
0	5	2	2	2	3	2.89
1	3	2	2	2	3	2.44
3	3.5	2	2	2.5	3	2.64
6	1	2	2	2	2	1.78
7	3	2	2	1	2	2.06
10	2	2	2	2	2	2.00

Table D.5: Approach Cranfield Flying Qualities Rating Scale

Law	Pilot A
0	3
1	4
3	3
6	2
7	2
10	3

Table D.6: Approach Bedford Workload Rating

Cooper Harper Ratings

This section contains the Cooper Harper ratings for the formation flying task (see table D.9).

Formation Cranfield Handling Qualities Rating

This section contains the Cranfield Handling Qualities Rating scale for the formation flying task can be found in table D.10.

Bedford Workload Ratings

The Bedford workload ratings can be found in table D.2 for the formation task.

Law	Pilot A
0	3 (app), 4 (flr)
1	1
3	1
6	1
7	1
10	1

Table D.7: Pilot Induced Oscillation Rating

PIO Ratings

The overall PIO ratings for the formation task can be found in table D.2.

Pilot	Eval No.	Law	V_{50}	$\dot{H}_{50}$	V_{td}	$\dot{H}_{td}$	X_{td}	Y_{td}
A	35	10	119.7	11.2	113.9	3.9	278	4.3
A	35	10	119.6	8.1	116.5	5.9	34	-1.8
A	36	3	120.6	11.4	117.0	4.6	411	14.1
A	36	3	114.2	8.2	115.6	5.6	-131	0.7
A	36	3	118.3	8.0	113.9	4.7	-68	5.8
A	37	1	117.2	12.6	113.7	2.7	-72	4.3
A	37	1	116.1	13.6	114.3	3.9	-66	7.9
A	37	1	119.4	11.2	114.9	5.0	-52	2.5
A	38	6	116.5	7.3	113.2	7.1	-122	1.2
A	38	6	119.9	11.3	113.7	2.8	400	-0.8
A	39	7	118.5	14.4	111.0	4.8	347	-2.7
A	39	7	119.4	11.8	113.0	4.8	107	8.1
A	40	0	119.0	12.6	112.3	3.7	184	7.5
A	40	0	120.0	11.6	114.5	4.5	-160	0.6
A	40	0	120.6	10.7	118.0	3.1	-192	1.8
E	41	6	112.7	17.9	108.2	4.3	-614	-3.3
E	41	6	109.2	7.3	109.9	5.2	-164	-0.8
E	41	6	120.2	22.5	118.6	8.8	-194	13.4
E	41	6	104.5	20.5	109.3	8.6	-1538	1.0
E	42	7	126.8	15.2	118.9	2.0	945	0.1
E	42	7	123.5	12.6	115.8	4.1	223	4.3
E	42	7	109.7	19.4	108.4	11.4	-1117	17.4
E	42	0	108.2	23.5	112.4	10.0	-793	9.5
E	43	10	122.1	5.5	118.2	2.9	313	12.3
E	43	10	124.3	9.1	118.9	4.1	263	3.5
E	43	7	110.9	22.9	109.5	12.1	-415	19.2
E	44	3	124.4	14.7	120.7	0.2	253	9.0
E	44	3	123.4	12.2	122.3	4.2	260	1.7
E	45	1	112.4	23.2	113.2	15.7	-436	3.4
E	45	1	120.8	9.3	119.5	3.2	0	-3.6
E	46	0	120.5	15.8	120.6	3.1	-298	9.4

Table D.8: Touchdown Performance Data

Law	Pilot A
0	4
1	4
3	3
6	5,5
7	3
10	4

Table D.9: Formation Cooper Harper Ratings

Law	Long Char	Lat Char	Dir Char	Trim	Speed	CFDHQR
Weighting	4	4	3	3	4	
0	5	4	2	3	4	3.72
1	4	3	2	2	4	3.11
3	3	3	2	2	4	2.89
6	5	3	2	2	5	3.56
6	5	3	2	2	5	3.56
7	2	3	2	2	3	2.44
10	4	3	2	2	3	2.89

Table D.10: Formation Cranfield Flying Qualities Rating Scale

Law	Pilot A
0	6
1	5
3	4
6	6,6
7	3
10	4

Table D.11: Formation Bedford Workload Rating

Law	Pilot A
0	4
1	2
3	2
6	3,3
7	1
10	2

Table D.12: Pilot Induced Oscillation Rating